AIRCRAFT AND AUTOMOBILE MATERIALS OF CONSTRUCTION

VOL. I

FERROUS MATERIALS

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VOL. I.

FERROUS MATERIALS

A TREATISE FOR AIRCRAFT, AUTOMOBILE, AND MECHANICAL ENGINEERS, MANUFACTURERS, CONSTRUCTORS, DESIGNERS, DRAUGHTSMEN, STUDENTS, AND OTHERS

BY

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PREFACE

THIS book has been written, principally for the benefit of the user of the various ferrous and non-ferrous materials employed in the construction of automobiles, aircraft, and general mechanical engineering work as distinct from the metallurgist.

Owing to the extent of the subject and to the rather wide scope of the work, it has been found necessary to divide the matter into two sections, each in a separate volume, the present one dealing entirely with ferrous materials, and the second volume with non-ferrous and organic materials.

The present work covers a wide range, and may be regarded as containing the more directly useful information and data from a large number of specialist books upon the subjects treated, supplemented by modern data, kindly supplied by the leading manufacturers in this and other countries, and by the inclusion of matter derived from the current and past proceedings of various societies and institutions.

The average user of materials, such as the aircraft or automobile constructor, is not greatly concerned with the metallurgical processes to which his metals have been previously subjected, but rather to their composition, strength, properties, and modes of heat and other treatment, etc., as received from the steel or other metal manufacturer.

To the student, the relationships between the theoretical and actual properties of materials as revealed by test will no doubt prove interesting, as also will the more practical applications of the materials themselves. The draughtsman and designer will find fairly full information upon the theoretical side of the subject of stresses and strains, and should be able, after perusal of the sections upon the behaviour of

materials under test, and of the various material specifications, strengths, compositions, etc., to choose materials suitable for any part or member, or for almost any purpose, with ease. The sections dealing with the theoretical sides of the subjects have been kept quite separate and tolerably complete, in order that the more practical material users may not be hampered too much by an admixture of theory and practice in selecting the information they desire.

Similarly, a section has been devoted to the machines and instruments used for testing materials, which is fairly complete in itself.

In planning out this work, it was considered advisable to include an introductory chapter dealing with the theory of stresses, strains, etc., in so far as they concern the properties of the materials discussed later in the book, in order that the designer, engineer, and constructor might appreciate the co-relationship between theory, testing and actual practice, and also in order to emphasize and explain the terms used later on throughout the book. Particular attention has been paid to the English and American specifications of materials for specific purposes, and it is hoped that the tabular matter covering the properties of practically all of the carbon and alloy steels used in practice, given in Chapters V. and VI. and in the Appendices, will prove useful in this respect.

The question of the various treatments to which materials are subjected, with definite objects in view, has also received attention both from the theoretical and practical points of view; many useful practical hints and recipes will be found throughout the book.

The subjects of heat treatment, furnaces and pyrometry have also been dealt with as fully as space allowed from the point of view of the works engineer and constructor.

The great difficulty in books of the present type, which have for their object the presenting to the reader of matter derived from various sources, on specialized subjects, etc., is to know just how much to include, and how much of the vast amount of information available to put aside; and in the present instance, only considerations of the present scope,

utility, and final size of the book, have limited the amount of matter selected from the very large quota available.

It is hoped that the author will have succeeded, at least to a great extent, in his object of presenting to the aircraft and automobile engineer, designer, constructor, draughtsman, student, and general user of materials, a really useful work, at a reasonable price, containing in two volumes only a brief but sufficiently clear and informative account covering the range of subjects indicated by the title.

The author would welcome any suggestions, information, etc., with a view to making this work more complete in later editions, and would be glad to have his attention directed to any errors which may have crept in, in spite of repeated and independent checking of the proofs.

In conclusion, the author takes this opportunity of expressing his thanks and appreciation to the numerous individuals, firms, and institutions concerned, who have contributed to the information and illustrations, in particular to the Aeronautical Society of Great Britain, the Institution of Automobile Engineers, the Institute of Metals, the Cambridge Scientific Instrument Co., the Foster Instrument Co. (Letchworth), Messrs. Firth and Sons (Sheffield), Messrs. Vickers, Ltd., Messrs. Edgar Allen (Sheffield), Messrs. Bruntons of Musselburgh, the Richmond Gas Stove and Meter Co. (Warrington), the Monometer Co. (Birmingham), Messrs. Accles and Pollock (Manchester), etc., to Dr. Hatfield for the use of several of the microphotographs shown in Chapters IV., V., and VI., and to Mr. Stubbs for information and loan of illustrations on the subject of drop-forging.

A. W. JUDGE.

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CHAPTER I

STRESS, STRAIN, AND ELASTICITY

WHEN a structure of any kind, such as a machine, engine, bridge, or similar object, is loaded in any manner—that is to say, when it is subjected to the action of forces—the various members, or parts, of the structure are said to be stressed under the influence of the loads. As will be seen, later, the stresses caused may be of various characters, such as tensile, compressive, or shearing, or a combination of two or three of these.

In order to determine the proportions, or the suitability of the structure for withstanding the loads, it becomes necessary to know two things, namely: (1) The amount and nature of the stress in each member; and (2) the properties of the materials of which the members are composed.

The former requirement necessitates a knowledge of the methods of analysis and of calculation in order to determine the nature and amount of the forces or stresses in the members, and the changes of form occurring under the influence of the forces; this portion of the subject is treated of in works upon the Strength of Materials.

The second side of the subject deals with the mechanical and physical properties of materials as determined by experience and experiment, and to the processes of treatment of the materials; it is known as the Properties of Materials.

The two subjects are to a certain extent interconnected, since the properties of the materials of members of a structure determine the degree and nature of the deformation under load, and in many cases the deformation governs the values of the stresses in the members. Examples of this co-relation may be seen in the case of ferro-concrete, composite structures of dissimilar materials, structures comprised of members having different factors of safety and subjected to different types of stress. Moreover, different materials such as different kinds of metals, metals of different degrees of hardness but of the same composition, timbers, fabrics, etc., behave in a very different manner under load, and the particular properties of each material when subjected to loading are the principal factors in strength calculations.

For determining the dimensions of any member of an engineering or aircraft structure it is not alone sufficient to know the strength properties under different kinds of loading, but also the endurance of the materials under wearing, weathering, and similar conditions.

Experimentally Determined Stresses.

Many cases occur in practice, in which not only the values, but also the nature of the stresses in particular structures cannot be estimated by known analytical methods, or can only be estimated upon uncertain assumptions, so that it becomes necessary to have recourse to methods of experiment in order to determine the stresses.*

In many cases, it is possible to test full-sized structures, members, or bodies, to destruction, making careful measurements of the deformations, loads, and manner of failure under conditions resembling those of actual practice; the information obtained is usually an invaluable guide in apportioning the final structure, member, or body.

Testing machines, such as those described in Chapter III., although primarily intended for testing the properties of the

* Alternative methods for finding the stresses in a loaded body or structure are given upon p. 239 *et seq.*

materials themselves, are often suitable for testing full-sized components; for example, automobile wheels and spokes can be crushed, aeroplane struts crippled, bracing wires, rods, and chains, pulled apart, and engine members such as connecting rods, crank-shafts, gear-wheels, and parts subjected to stress, tested to destruction.

Many structures are either too large, or would require special testing machines of an elaborate kind to test them to destruction, but in all such cases the behaviour under their own systems of loading can be ascertained, either by loading them directly, or, if this method is prohibitive for reasons of cost and inconvenience, scale models may be made and tested under similar conditions of loading.

It is, of course, necessary to know the laws governing the application of model results to the full-sized structure; many examples have occurred, in the past, of models working or behaving satisfactorily, whereas the full-sized structure or machines made from these models were failures.

Thus, supposing, for example, it is found that a wire of diameter d will support a spherical (or, indeed, any other shape of) weight of diameter D quite safely; next, suppose that a wire of ten times the diameter d is taken and that a weight of ten times the diameter D (or the linear dimensions) is hung upon it.

The tensile stresses in the two cases will not be the same but as 1 is to 10, owing to the fact that the weight varies as the cube, whereas the cross-sectional area varies as the square of the linear dimensions.

In all structures,* in which the whole, or part, of the stresses is due to the weight of the structure itself, the stresses will be greater for larger structures of similar shapes; it may be here mentioned that the ultimate or maximum span† of cantilever and other bridges and similar structures is limited by weight considerations, and that each design of structure

* In all weight loaded structures, such as beams, the stresses in similar designs vary directly as the linear dimensions.

† An example of limiting bridge span is given by the case of the Firth of Forth cantilever bridge.

has a definite limiting size or a given working stress and material. The increase in this "limiting" value is only possible by employing materials of greater strength-weight ratio.

In the case of machines, in which the accelerating forces are the limiting factors (as, for example, in the case of petrol and other high-speed reciprocating engines). these forces are proportional to the linear dimension d, the mass d^3, and the square of the speed, or revolutions per second, N^2—that is, to the product d^4N^2. The bending moments in similar machines at the same places will be proportional to d^5N^2, and the stresses to d^2N^2. Hence in similar machines, if the accelerating-force stresses are to be the same in value, the product d^2N^2 must be the same; that is, the speed must decrease as the size increases, or revolutions per minute should vary inversely as the linear dimension.

In aeronautical structures the loads governing the working stresses are in most cases due to the relative air speeds, as well as the total weight; and it is therefore necessary to test such structures under similar conditions of air-pressure, resistance, and weight. A common test for machines of a standard quantity production, or new, type is to place the machine upside down upon trestles under the centre section portion and to load the wing and tail surfaces with bags of sand or shot, under approximately the same load distribution as that occurring in flight. The resistance effect is also approximated to, by means of horizontal cables pulling upon the wings.

The factor of safety, in such cases, is given by the difference between the total breaking load and the wing structure weight, divided by the machine's flying weight. The methods of calculating the stresses in girder structures, such as bridges, built-up beams, aeroplane wing and body-bracing systems, and other similar structures, are usually based upon the methods of continuous beams and pin-joints.

The former method assumes that the points of support of the flange members or rails are in the same line, or in a definite disposition; any subsequent deflection or movement of

the supports appreciably alters the values of the stresses. The pin-joint method assumes that the junctions of various members are frictionless pin-joints and the forces in the members are estimated accordingly; in practice, the joints are usually rigid, and, as in the case of an aeroplane wing-spar or longeron, members are often continuous through the "joints." The forces, due to rigidity and continuity of the joints, are appreciably different from those deduced from the pin-joint method. Here, again, experiment comes to the aid, and the necessary corrections for rigidity and continuity can be determined by loading a scale model of the structure to the elastic limit, or breaking-point.

Numerous other examples might be cited, but the above cases will serve to emphasize the importance of experimental tests and verifications; reference* is also made in Chapter III. to certain indirect experimental methods of determining the stresses and strains in loaded bodies and structures.

Stress.

When two bodies, or parts of the same bodies, transmit, or are subjected to, a force, the equal and opposite action and reaction which occurs between the two bodies, or parts, constitutes a *stress.*

The interaction, or mutual reaction, which takes place between the two parts of a body, divided by an imaginary surface, is said to constitute a *state of stress.*

Thus, in the case of strut, under compression, if any imaginary cross section be taken there is a mutual push between the parts lying upon opposite sides of this section, and a state of stress exists there.

A stress acting at a surface is distributed over it, either uniformly, or otherwise. If uniformly distributed each unit of area of the surface bears the same load, or is subjected to the same force, and the *intensity of stress* at any point is obtained by dividing the whole load, or force, by the whole area of the surface.

* P. 239 *et seq.*

If A represents the whole area, and P the total force, then for a uniformly distributed stress the intensity is given by—

$$\frac{P}{A}.$$

If the distribution of stress is not uniform the intensity of stress at any particular place may be found very approximately by dividing by any small area around the point the force upon that small area.

Thus if δA represent a small area around any point on a surface, at which a state of stress exists, and δP be the force upon that area, then the intensity of the stress at that point is—

$$\frac{\delta P}{\delta A}.$$

If P is given in pounds or tons, and A is in square inches, the intensity of stress will be in pounds per square inch or tons per square inch respectively.

If P is given in kilogrammes, and A is in square millimetres, or square centimetres, then the intensity of stress will be in kilogrammes per square millimetre or per square centimetre respectively.

For example, if a weight of 3 tons is hung upon the lower end of a uniform rod of $1\frac{1}{2}$ inches diameter, the intensity of the stress produced across any section will be given by—

$$p = \frac{P}{A} = \frac{3}{\frac{\pi}{4}(1\frac{1}{2})^2} = \frac{3}{1{\cdot}766} = 1{\cdot}70 \text{ tons per square inch.}$$

Types of Stress.—There are three principal kinds of stress which can occur—namely, tensile, compressive, and shear—of which the former two are known as simple stresses. and occur normally to the surface, whilst the latter stress occurs along the surface. or tangentially.

When the normal stress consists of a pull, the stress is a tensile one, and the portions lying upon the two sides of the surface tend to directly recede from each other.

When the stress is a push, the stress is compressive, and the two portions tend to approach.

Shear stress exists between two parts of a body, when they exert equal and opposite forces upon each other in a tangential direction; it tends to make one part slide over the other.

Besides the above three types of stress, a body may be subjected to more than one type of stress; in this case the stress is termed a complex one. Every complex stress can be split up into simple component stresses.

Examples of the different types of stress considered are illustrated diagrammatically in Fig. 1.

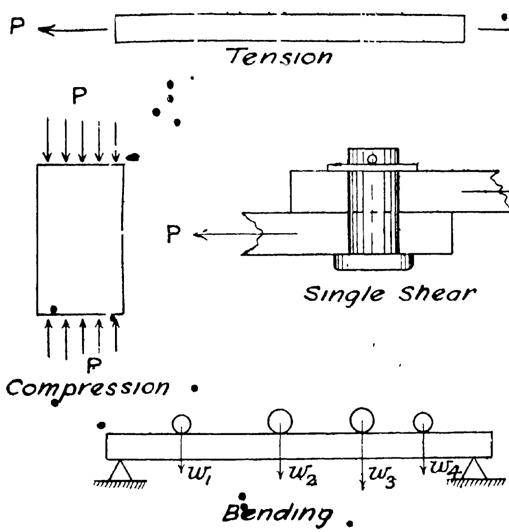


FIG. 1.—TYPES OF MECHANICAL STRESSES.

Strain is a technical term for expressing the change of form or shape, produced by stress.

Tensile strain, caused by a tensile stress, consists of an elongation in the direction of the pull, accompanied by a lateral contraction perpendicular to the elongation direction.

Compressive strain consists of a shortening or contraction in the direction of the push, accompanied by a lateral bulging or expansion in each direction at right angles to the former. If x denotes the longitudinal change in length, upon a

specimen of original length l, then the ratio $\frac{x}{l}$ measures the strain produced, whether tensile or compressive.

Shear strain consists of a tangential sliding of the parts under shear stress, in their direction. It is usually measured by the angle ϕ, shown in Fig 28.

Elastic Materials. (Hooke's Law.)

An elastic material is one for which the strain disappears when the stress is removed. Most materials, such as metals, timber, glass, and similar substances, are very nearly per-

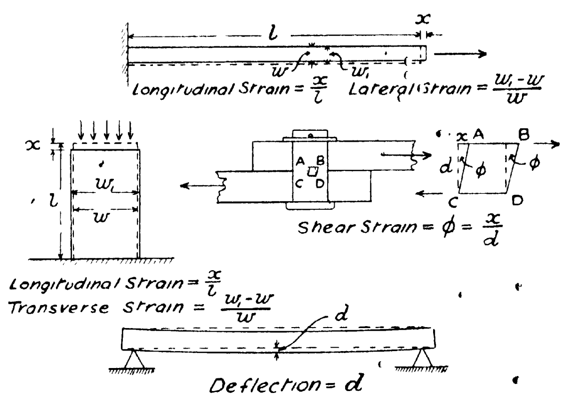


FIG. 2.—TYPES OF MECHANICAL STRAIN.

fectly elastic for small stresses, up to a limiting value for each material.

For example, in the case of mild steel, the material is elastic for stresses up to about 0·60 of the stress which would completely break or rupture the material.*

This limiting value of the stress, at which elasticity just ceases, is known as the *Elastic Limit.* Above this value of the stress the strain produced will not disappear when the stress is removed; the strain is then termed a *Permanent Set.*

The elastic limit varies for each material, and is more sharply defined in some cases than in others: thus in the case

* This is termed the Ultimate Stress, or Strength.

of mild steel, the elastic limit is readily discernible from the fact that the strain increases more rapidly for a given stress increase above this limit. For cast iron, copper, and aluminium, there is no true elastic limit and the stress and strain increase

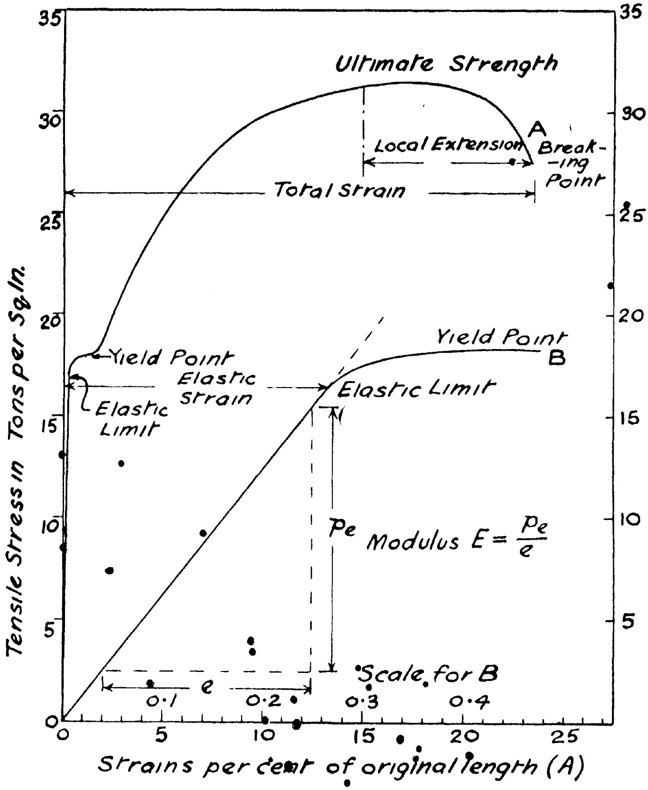


FIG. 3.

nearly at the same rate right up to the breaking point, which is fairly sudden. Fig. 3 represents graphically the relation between stress and strain for mild steel. It has been found that for elastic materials stressed within the elastic limit, *the strain is proportional to the stress producing it.* This is known

as Hooke's law. For the case of a simple tensile stress, if a given pull causes a certain longitudinal extension, then twice this pull will cause twice this extension, three times the pull three times the extension, and so on, provided that the total pull does not cause the stress to exceed the elastic limit.

Mathematically Hooke's law may be expressed in the following form for either tension or compression—namely:

$$\frac{x}{l} = \text{E}\left(\frac{\text{P}}{\text{A}}\right) = \text{E} \cdot p$$

where l = original length of the piece, x the change of length due to a load P, and A the cross-sectional area. $p = \frac{\text{P}}{\text{A}}$ is the stress, or force per unit area.

E is a constant, which is known as the Elastic, or Young's Modulus, and its value depends upon the particular material under consideration; this constant may be defined as the ratio of longitudinal stress to strain.

$$\text{Thus E} = \frac{p}{e} \text{ where } e = \frac{x}{l} = \text{the strain.}$$

If the stress be given in tons or pounds per square inch, then the Elastic Modulus should be expressed similarly. The units for $\frac{x}{l}$, the strain, are immaterial, since it is a ratio, but they must be consistent for both x and l.

For iron and steel E is about 13,000 tons per square inch or about 30,000,000 pounds per square inch. Thus a stress of 1 ton per square inch will produce an extension or contraction of $\frac{1}{13000}$ of the original length in the case of iron or steel.

The working stress for mild steel under steady load conditions is about 7 tons per square inch; the strain produced by this stress will be $\frac{7}{13000}$, or about $\frac{1}{1900}$ part of an inch per inch length of specimen.

It will be seen, then, that the elastic strains occurring in engineering work are very small indeed.

TABLE I.

VALUES OF MODULI OF ELASTICITY E.

Material.	*E. Pounds per Square Inch.*	*Material.*	*E. Pounds per Square Inch.*
Cast iron, white ..	23,000,000	Aluminium, sheet	13,500,000
Cast iron, grey .. .	15,000,000	Brass, cast ..	8,930,000
Wrought-iron bars ..	29,000,000	Brass, rolled ..	11,500,000
Wrought-iron plate ..	27,000,000	Copper, cast .	9,000,000
Wrought-iron wire ..	25,000,000	Copper, rolled ..	12,000,000
Mild steel	30,000,000	Copper wire .	16,000,000
Cast steel (untempered)	30,000,000	Gun-metal ..	10,000,000
Cast steel (tempered) ..	36,000,000	Delta metal, cast	12,000,000
Tool steel .. .	40,000,000	Delta metal, rolled	13,000,000
Rivet steel	30,000,000	Phosphor bronze	14,000,000
Steel plates ¼ to ½ per cent.		Aluminium bronze	15.500,000
carbon	31,000,000	Lead	2,500,000
Steel castings	30,000,000	Pine*	1,600,000
	20,000,000	Oak*	1,450,000
Aluminium, cast ..	12,500,000	Leather .	25,000

Transverse Strain.

The lateral or sideways contraction of a member, or specimen, under tensile stress, is a definite proportion of the longitudinal strain.

The ratio, $\dfrac{\text{transverse strain}}{\text{longitudinal strain}} = \sigma$, is known as Poisson's Ratio, and for metals its value lies between $\frac{1}{3}$ and $\frac{1}{4}$.

TABLE II.

VALUES FOR POISSON'S RATIO.

Material.	*Value of Poisson's Ratio.*
Mild steel	0·29
Wrought iron	0·27
Cast iron	0·25
Brass (cast)	0·33
Copper (cast)	0·33
Glass (flint)	0·24

Hooke's Law for shear stress and strain may be written symbolically as—

$$\frac{\text{shear stress}}{\text{shear strain}} = \frac{q}{\phi}$$

* For other timbers see Vol II. of this work, entitled "Non-Ferrous and Organic Materials."

where C is a constant for each material, and is known as the *Modulus of Rigidity*. Its value, which is usually determined by torsion experiments, may be taken as being about two-fifths of the Elastic Modulus.

TABLE III.

VALUES OF MODULI OF RIGIDITY C.

Material.	*C. Pounds per Square Inch.*	*Material.*	*C. Pounds per Square Inch.*
Cast iron*	7,600,000 6,300,000 5,000,000	Copper, rolled ..	4,700,000 6,500,000
Wrought iron ..	10,500,000	Brass	4,500,000 5,100,000
Iron boiler plates ..	14,000,000	Bronze	5,100,000 6,000,000
Mild steel plates ..	13,000,000 to 14,000,000	Gun-metal ..	4,250,000
		Phosphor bronze.	5,150,000
Cast steel (untempered)	12,000,000	Aluminium bronze	5,600,000
		Silver	4,000,000
Cast steel (tempered)	14,000,000	Gold .. .	4.700,000
		Platinum .	9,000,000
Copper, cast ..	4,300,000 5,100,000	Flint glass ..	3,300,000 3,400,000

Bulk, or Volume, Modulus.

When a solid is subjected to three simple pushes, of equal intensity applied in three directions, if the material is homogeneous†—that is to say, has equal properties in all directions—it suffers a contraction of volume only.

If the change of volume v, due to three simple stresses of intensity p, acting in three directions, mutually at right angles, and V is the original volume, then within the elastic limit, the volumetric strain is proportional to the stress p—that is to say—

Volumetric strain $= \frac{v}{V} = \frac{p}{K}$ where K is a constant known as the *Bulk*, or *Volume, Modulus*.

* The values given are for white, medium, and grey cast irons respectively.

† A material having unequal properties in different directions, such as timber, is said to be heterogeneous; certain of the crystals belong to this class.

The linear strain will be—

$$\frac{1}{3}\frac{v}{V}=\frac{p}{3K}.$$

The value of K may be determined experimentally by measuring the volume change when the body is placed in a liquid to which pressure is applied, or it may be estimated from the other elastic constants, from the relation given in the next paragraph.

TABLE IV.

VALUES OF BULK MODULUS K. (Pounds per square inch.)

Material	*K.*
Water	320,000
Mercury	7,850,000
Glass (flint)	4,950,000 to 5,900,000
Brass	14,300,000 to 15,500,000
Copper	24,000,000
Cast iron	13,700,000
Wrought iron	20,700,000
Steel	25,200,000

Relation between Elastic Constants.

It can be shown, analytically, that E, C, and K are related in the following manner—namely:

$$\frac{1}{E}=\frac{1}{3C}+\frac{1}{9K} \text{ or } E=\frac{9KC}{3K+C}.$$

For the transverse contraction, where σ denotes Poisson's Ratio—

$$\sigma=\frac{3K-2C}{6K+2C}.$$

For a material such as rubber, in which the longitudinal extension is great compared with the lateral contraction, (rubber extends readily, but is compressed with difficulty), the value of σ will be much smaller than in the case of a metal. The limiting value of σ will be seen to be $\frac{1}{2}$; it cannot be greater than this.

Another useful relation between the constants is—

$$C=\frac{\sigma E}{2(\sigma+1)}.$$

Work Done in Elastic Strain. Application to Springs, etc.

For simple tension, or compression, in the case of an elastic material, the work done per unit area, per unit length, is given by—

$$\text{Work done per unit volume} = w = \text{mean stress} \times \text{strain}$$
$$= \frac{p}{2} \cdot \frac{x}{l} = \frac{p^2}{2E}, \text{ for } \frac{p}{E} = \frac{x}{l}.$$

The quantity $\frac{p^2}{2E}$ (termed the *Resilience*) measures the capacity for storing work in consequence of the strain, and this energy can be restored when the strain is relaxed.

Thus in the case of metal springs, the most suitable materials are those having the highest resiliences or values $\frac{p^2}{2E}$ under working stress conditions. Since the value of E is practically constant for similar engineering metals, it follows that the best material for tension, compression, or beam springs, from the weight and bulk point of view, is that having the highest elastic limit, or working stress. The alloy steels, such as chrome-vanadium, silicon, and nickel chrome, are about the best for this purpose.*

India-rubber, for its weight, can store up considerably more energy than any other commercial material. Thus for hardened cast steel the working resilience per cubic inch is about 500 inch pounds, and for good india-rubber it is about 200 inch pounds. The relative weights per cubic inch are as $8\frac{1}{4}$ to 1, and the respective resiliences for india-rubber and steel, in foot pounds per pound weight, are roughly 500 and 15.

The work done per unit volume, in elastic shearing action, is given by—

$$\frac{q^2}{2C}.$$

The work done by a load upon a given structure is equal to the product of the load and the deflection of the structure in the direction of the load; this work done must also be

* Fuller particulars of spring materials are given on pp. 380 to 384.

equal to the sum of the strain-energies (as defined above) of the members comprising the structure.

This principle is a valuable one in connection with the determination of the stresses in complex structures, and has been applied to such examples as aeroplane wing bracings with different deflections at different places along the spars, bridge-trusses, and redundant frames; the method is known as the Strain-Energy one. It is, however, outside of the scope of the present volume to discuss problems which rightly belong to the subject of the strength of structures.

Table V. (p. 16) gives the average values for the tensile, compressive, and shearing resiliences of the materials indicated; in each case the resilience is given in inch pounds per cubic inch of the material.

Simple Stresses (Inclined Sections). Fig. 4.

Consider the case of either a tensile or compressive force acting upon a piece of material. If the area of the cross-section AB be A square inches, and the total pull or push be P pounds, then the intensity of stress over AB, is given by—

$$p = \frac{P}{A} \text{ pounds per square inch.}$$

There is no tangential force along AB.

The intensity of the normal tensile force over any section CD, inclined at an angle θ, to AB, for the case of two tensile pulls is given by—

$$f_t = \frac{P \cos \theta}{\dfrac{A}{\cos \theta}} = \frac{P}{A} \cos^2 \theta = p \cos^2 \theta.$$

The tangential or shear stress over CD is given by–

$$q = \frac{P \sin \theta}{\dfrac{A}{\cos \theta}} = \frac{P}{A} \sin \theta \cos \theta = \frac{p \sin 2\theta}{2}.$$

* For fuller information the reader is referred to "The Theory of Structures," by Professor A. Morley, chap. xiv., "Deflection and Indeterminate Frames."

TABLE V.

RESILIENCES OF DIFFERENT MATERIALS. (Perry.)

Material.	Tension.			Compression.			Shear.		
	f_t. Pounds per Square Inch.	$E \times 10^6$. Pounds per Square Inch.	$f_t^2/2E$. Inch Pounds per Cubic Inch.	f_c Pounds per Square Inch.	$E \times 10^6$. Pounds per Square Inch.	$f_c^2/2E$. Inch Pounds per Cubic Inch.	f_s. Pounds per Square Inch.	$C \times 10^6$. Pounds per Square Inch.	$f_s^2/2C$. Inch Pounds per Cubic Inch.
Cast iron	3500	14–23	3	10,500	14–23	12	2700	5·0–7·6	5
Wrought iron	24,000	29	10	24,000	21	10	20,000	10·5	19
Mild steel	35,000	30	20	35,000	21–25	15	26,500	11	32
Mild steel, hardened	70,500	30	83	—	—	83	53,000	11	128
Cast steel, unhardened ..	80,000	30	107	—	—	—	64,000	11	186
Cast steel, hardened ..	190,000	36	501	—	—	—	145,000	13	809
Copper	4300	15	0·62	4000	17·1	0·5	2900	5·6	0·75
Brass	6950	9·2	2·62	6500	15·3	1·23	5200	3·4	4·00
Gun-metal	6200	9·9	2·00	6000	15·0	1·80	4150	3·7	2·33
Phosphor-bronze glass ..	19,700	14	13·85	20,000	14·0	14·3	14,500	5·25	20·0
Glass	4500	8	1·26	10,000	5·8	8·6	—	3·3–3·9	—
Fir	10,000	1·5	5	6000	1·5	1·3	—	0·1–0·7	—
Oak	14,500	1·3	4	10,000	1·3	3·85	—	—	—

Note.—f_t, f_c, and f_s, are the tensile, compressive, and shear stresses at the elastic limits.

It will be seen that the maximum value of p_s the shear stress, is $\frac{p}{2}$, and occurs when $\sin 2\theta = 1$ or $\theta = 45°$.

It is of interest to note that the planes of cleavage or fracture of pieces in tension or compression are approximately

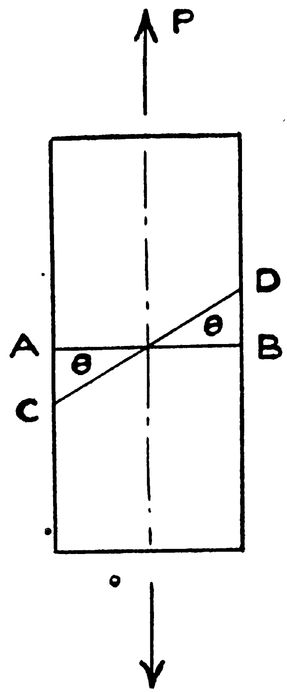


FIG. 4.—SIMPLE TENSILE STRESS.

at angles of 45° to the axis. The mutual frictional resistance due to the relative sliding of the surfaces somewhat modifies this angle, however, in actual cases.

Complex Stresses.

When a body is subjected to forces causing normal or shear stresses in known directions—that is to say, when it is under a complex system of stresses—the effect caused will be

exactly similar to that produced by three simple tensile or compressive stresses acting in three directions mutually at right angles.

Each of these equivalent stresses is termed a "*principal stress*," and the planes normal to which they act are known as "principal planes," the directions of the stresses lying along the "*axes of stress*."

One of the principal stresses at any given point in the body is always greater than any other stress at that point,

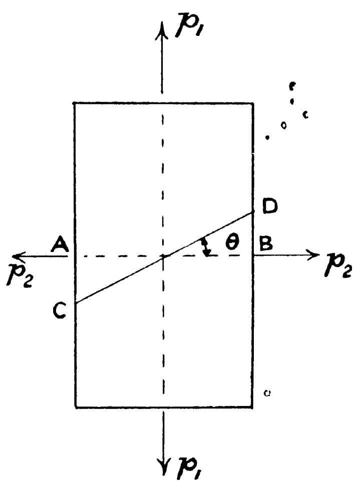


FIG. 5.

irrespective of direction, and another of the principal stresses is always a minimum for all stresses at that point.

The state of stress across any plane can be found by algebraic addition of the components of the complex stresses along and normal to the plane.

(1) If a body be subjected to two simple tensile* stresses, acting in directions at right angles, as shown in Fig. 5, the stresses upon any inclined section CD will be as follows—namely:

* The same reasoning will apply to the case of compressive stresses.

$$\text{Normal stress } f_t = p_1 \cos^2 \theta + p_2 \sin^2 \theta.$$

$$\text{Tangential stress } q = p_1 \frac{\sin 2\theta}{2} + p_2 \frac{\sin 2\theta}{2}.$$

The maximum tangential stress occurs when $2\theta = 90°$ or $\theta = 45°$ and its value is $\frac{p_1 - p_2}{2}$, the corresponding value of the normal stress on CD being $\frac{p_1 + p_2}{2}$.

(2) **Simple Shear.**—If, however, one of the forces is a push, whilst the other is a pull, then, either p_1 or p_2 will be negative.

Calling tensile forces positive, and compressive ones negative, then the normal force upon CD becomes—

$$p_N = \frac{p_1 - p_2}{2},$$

and when $p_1 = p_2$ there is no normal force.

The only stress to which CD is subjected will then be a shear stress of intensity equal to p_1 or p_2. So that a state of

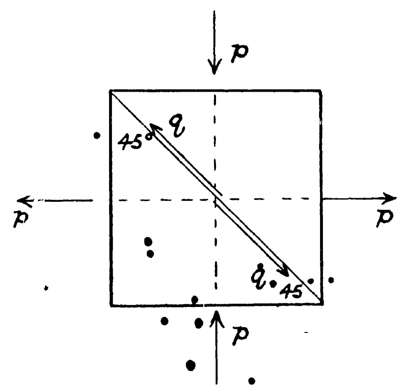


FIG. 5A.

simple shear may be produced by two equal, but opposite in sign, principal stresses acting at right angles, and the intensity of the simple shear stress is equal to either of these, and occurs upon planes at 45° to the principal stress directions, as shown in Fig. 5A.

It can also be shown as follows, that every tangential stress, no matter how it is originated, must be accompanied by an equal tangential stress acting along a plane at right angles to the other. If an indefinitely small cube ABCD (Fig. 5B), under the influence of shearing stress q, along parallel sides

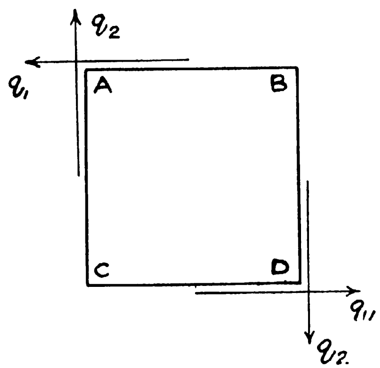


FIG. 5B.

of the material, be considered, then a little consideration will show that no possible arrangement of normal stresses upon the faces of the cube can balance this shear-couple. This can only be balanced by an equal and opposite shearing stress q_2 along the sides of the cube at right angles to the other stress q_1.

Combined Normal and Shear Stresses.

In connexion with the stresses existing in beams, the case of a simple shear stress, and a normal stress of either compression or tension, occurs, as depicted in Fig. 6. It is required to find the resultant normal stress, equivalent to these stresses.

Considering indefinitely small horizontal and vertical sections, BC and AC respectively, let p be the intensity of the normal stress, and q that of the shear stress perpendicular to AB, and along CB respectively. As previously shown, the shearing stress q along CB will be accompanied by an equal shearing stress q along AB.

If AC be the plane perpendicular to which the resultant stress r (the magnitude and direction of which it is required to find) acts, then the conditions for equilibrium can be

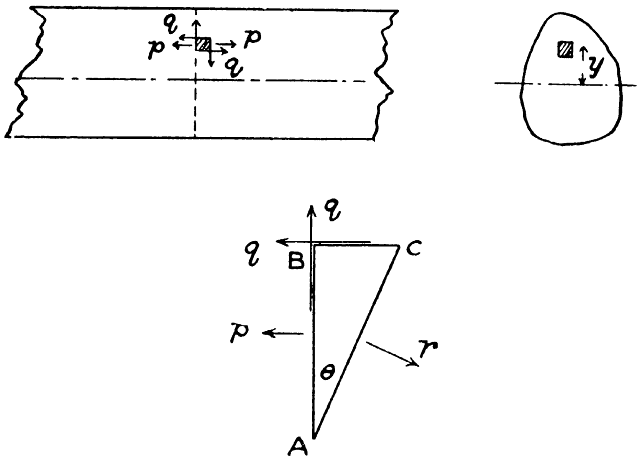


FIG. 6.—STRESSES IN BEAMS.

obtained by taking resolutes along AB and AC, and may be expressed as follows—

$$(r - p) \cos \theta = q \sin \theta$$
$$q \cos \theta = r \sin \theta.$$
$$\text{Whence } \tan 2\theta = \frac{2q}{p}$$
$$\text{and } r = \frac{p}{2} \pm \sqrt{q^2 + \frac{p^2}{4}}.$$

The maximum, or principal, stress is given by the positive root value, and the minimum stress by the negative value. It will be seen that these two resultant stresses act on planes, mutually at right angles.

It also follows from what has already been shown, that the maximum shearing stress values act along planes inclined at 45° to those of the principal stresses; its value is—

$$\tfrac{1}{2} \sqrt{4q^2 + p^2}.$$

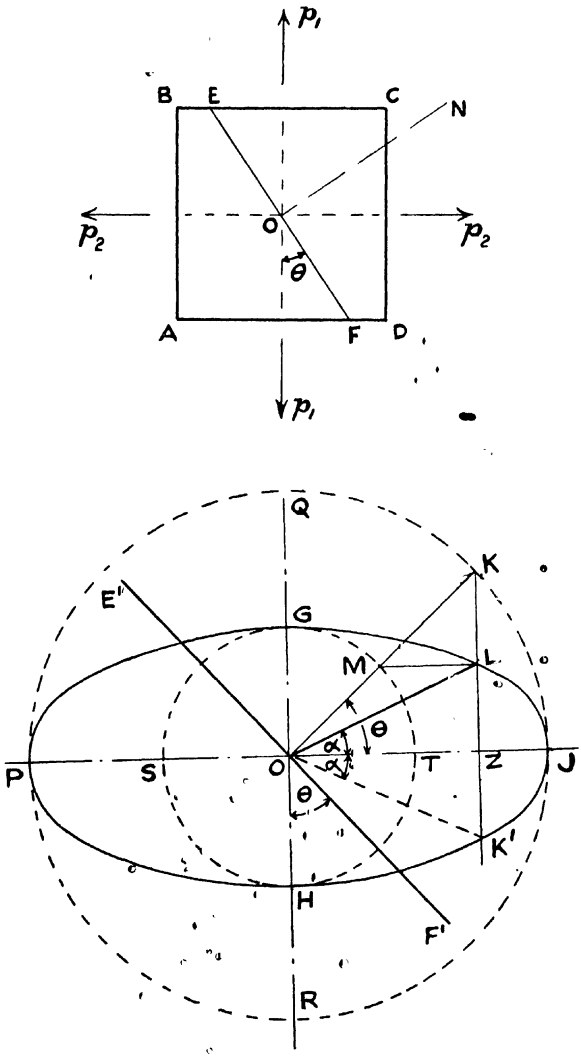


FIG. 7.—THE STRESS ELLIPSE.

The Stress Ellipse.

A convenient graphical method of obtaining or of representing the resultant stress on any plane of a body which is subjected to two principal or simple stresses (tensile or compressive) is illustrated in Fig. 7.

In the upper diagram a body is supposed to be subjected to the action of two simple stresses, p_1 and p_2, as shown. The stress ellipse enables the magnitude and direction of the resultant stress upon any plane such as EF to be at once determined.

Let two concentric circles, PQJR and SGTH, be described with radii OQ and OG respectively proportional to the simple stresses p_1 and p_2. Draw E^1F^1 parallel to the plane EF in the upper diagram, and OK perpendicular to E^1F^1 Draw KZK^1 perpendicular to POJ, and through M draw ML perpendicular to QOR. Then the point L lies upon an ellipse PGJH, and OL represents in magnitude and direction the resultant stress upon the plane E^1OF^1 due to the simple stresses p_1 and p_2. For any other inclination, a corresponding point such as L can be found by a similar construction, lying upon the stress ellipse, giving the corresponding resultant stress for that inclination.

If the simple stresses are unlike in sign—that is to say, if one is tensile and one compressive—then the dotted line OK^1 will represent the resultant stress.

More General Case of Principal Stresses.

The case of a single normal stress and two equal shear stresses at right angles has already been considered on p. 20.

It is now proposed to deal with the case of two normal stresses and mutually perpendicular equal shear stresses as shown in Fig. 8, in which PQRS represents a very small block of the material of unit thickness, subjected to two simple tensile stresses p_1 and p_2, and to two equal shearing stresses of intensity q acting at right angles

The directions of the principal planes, and the values of the normal principal stresses are required.

If EF be a principal plane at θ to the direction of p_1, and if p be a principal stress on this plane, then the conditions of

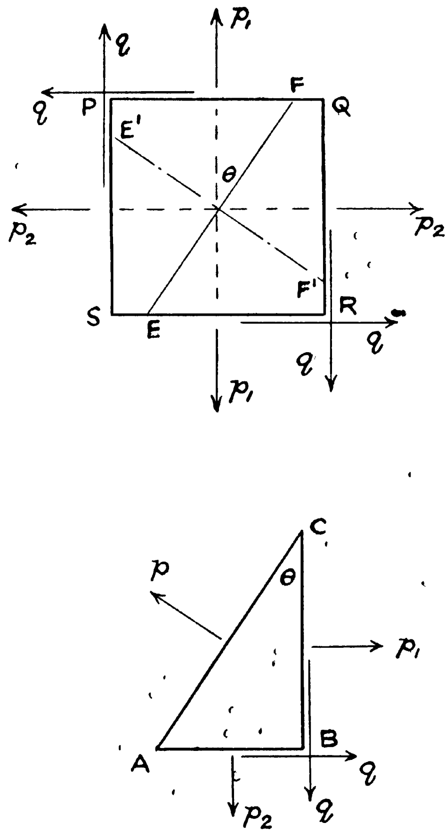


FIG. 8.

equilibrium of any small triangular wedge such as ABC, which has its sides parallel to the sides of the rectangular block and to EF respectively, will be as shown in the lower diagram of Fig. 8. It will be seen by resolving the stresses, equating, and simplifying, that—

$$\tan 2\theta = \frac{2q}{p_1 - p_2},$$

$$\text{and } p = \frac{p_1 + p_2}{2} \pm \sqrt{\frac{(p_1 - p_2)^2}{4} + q^2}.$$

The directions (θ) and magnitudes (p) of the principal stresses are thus determinate.

The planes EF and E^1F^1 of the principal stresses are at right angles, and the greater value of the principal stress corresponding to the positive root occurs on the plane EF, whilst the negative root value of p corresponds to the smaller principal stress occurring on the plane E^1F^1.

The maximum shear stresses, as before, occur upon planes inclined at 45° to the principal planes, and the value of the maximum shear stress is—

$$q_m = \frac{p - p_1}{2} = \sqrt{\frac{(p_1 - p_2)^2}{4} + q^2}.$$

Properties of Beams.

In the following considerations, the more important properties of beams will be briefly studied, from the point of view of the subject of the properties of materials, since many of the materials are employed in automobile and aircraft work, in the form of beams; moreover, beam tests upon representative samples of certain materials, such as those of cast iron, timber, etc., form an important branch of the subject of testing of materials.

A knowledge of the stresses and deformations of loaded beams is essential to a correct understanding of the properties of materials employed in the form of beams; in the following considerations, the principles, and results deducible from same, will be considered, in many cases without the analytical proofs.

Bending Moments and Shearing Forces.

When a beam, loaded in any manner, is supported at one or more places, then the algebraic sum of all of the vertical load components to the right, or to the left, of the section

considered, is termed the *Shearing Force*, usually denoted by the letters S.F., at that section. Thus, in Fig. 9, which represents a beam supported at each end and loaded irregularly as indicated by the irregular area NPMA, if any section

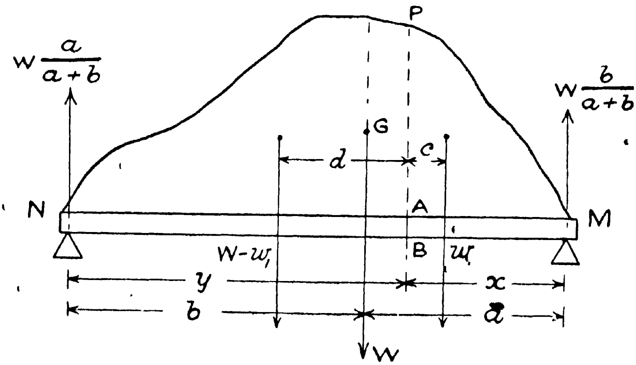


FIG. 9.

AB be taken, then the S.F. at this section will be given by the algebraic sum of the loads, say, to the left. If G denote the centre of gravity of the load, then the reactions of the supports at M and N respectively will be $W \cdot \frac{b}{a+b}$ and $W \cdot \frac{a}{a+b}$.

If w_1 denotes the load represented by the area MPB, then—

$$\text{S.F.} = W \cdot \left(\frac{b}{a+b}\right) - w_1 ;$$

or taking the forces to the right of the section AB—

$$\text{S.F.} = -W \cdot \left(\frac{a}{a+b}\right) + (W - w_1) = \frac{W \cdot b}{a+b} - w_1.$$

These forces, to the right, or to the left, must of course be equal.

Consider, next, the moments of each of the forces or loads acting about any section such as AB. The algebraic sum of the moments of the forces taken about the given section, to the right, or to the left, of the section, is termed the *Bending Moment* about that section (usually denoted by the letters B.M.).

Referring again to Fig. 9, let the distances of the C.G.'s of the loads MPB and PBN from the vertical line PB be denoted by c and d respectively, and the distances of the supports M and N from AB be denoted by x and y respectively.

Considering moments to the left of AB, first—

$$\text{Then the B.M. at AB} = \text{W} \cdot \left(\frac{b}{a+b}\right) \cdot x - w_1 \cdot c,$$

or considering moments to the right—

$$\text{B.M. at AB} = -\text{W} \cdot \left(\frac{a}{a+b}\right) y + (\text{W} - w) \cdot d.$$

Each of these expressions must be the same, since the beam is in equilibrium under the forces acting.

It is usual to define *positive shearing forces* as those which tend to *shear the right-hand portion* of the beam *upwards*, and *negative* for the *left hand downwards*.

Positive bending moments are those which tend *to bend the beam*, in such a manner that it is *concave downwards*. It will be seen that this corresponds with an *anti-clockwise B.M.*, with the usual beam arrangement.

From the simple example shown in Fig. 9, the definition of positive and negative B.M.'s and S.F.'s may be readily followed.

B.M. and S.F. Diagrams.

If the B.M. be estimated at several places along the beam, and ordinates be set up proportional to the B.M.'s at these points, the curve formed by joining up the extremities of these points is known as the *B.M. Diagram*.

In the case of a number of isolated loads, it is only necessary to find the B.M. values at the points of application of the loads, and to join up the B.M. ordinates by straight lines.

A convenient method of constructing the B.M. diagram for the above case is to draw the B.M. diagrams for each of the loads separately, and then to add algebraically the respective ordinates, as shown in Fig. 10.

Similarly, the S.F. diagram is constructed by setting up ordinates proportional to the S.F. at each place along the

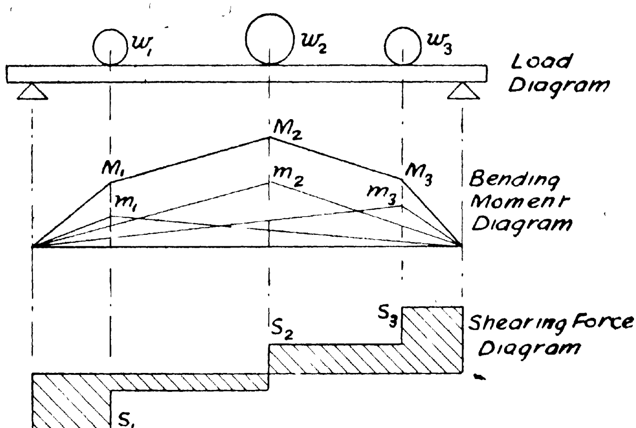


FIG. 10.

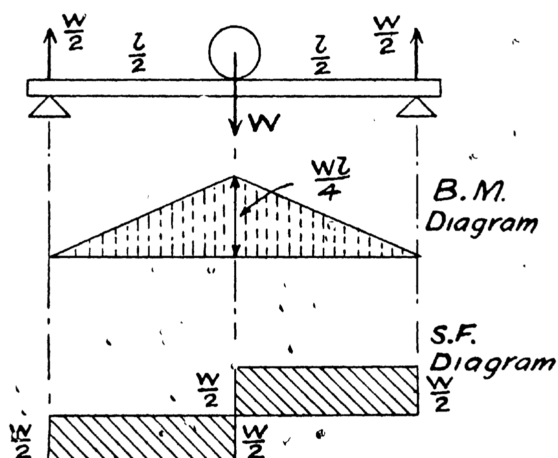


FIG. 11.

beam. The S.F. diagram is shown in Fig. 11 for the case of a simple beam supported at the ends and loaded in

between. It will be observed that at the point of loading the S.F. changes sign, whilst at the ends it changes value abruptly; this is due to the fact of the load being theoretically applied at a point, whereas in practice the load would be distributed over a finite length of the beam, and the change of S.F. would then be more gradual, being represented by an oblique instead of a perpendicular line.

The S.F. diagram for the case of isolated single loads, as shown in Fig. 10, may be constructed, similarly to the B.M. diagram, by adding algebraically the ordinates of the S.F. diagrams for the loads considered separately.

For distributed loads, the B.M. diagram is always a curve, over the distributed portion; if the distribution is uniform, it is a parabolic curve. The S.F. diagram in this case consists of an oblique straight line.

Examples of B.M. and S.F. diagrams for the more common cases of loaded beams, which occur in practice, are shown in Figs. 12 and 13, together with the maximum values of the B.M.'s, S.F.'s, and deflections.

Graphical methods for constructing the B.M., S.F., slope, and deflection diagrams for beams loaded in any manner,* are given in the author's "Design of Aeroplanes" (Selwyn and Co., London).

The Stresses in Beams.

A study of the internal stresses in the case of a loaded beam necessitates a knowledge of the B.M.'s and S.F.'s at all points along the beam; the methods of obtaining these quantities have already been considered.

A rough general idea of the stresses acting in a beam under load may be obtained by considering the case of a beam supported at its ends and loaded in the middle, as shown in Fig. 14 (A).

It will be seen that the upper side tends to shorten, or compress, whilst the lower side tends to lengthen, or extend,

* Also see "The Strength of Materials," E. S. Andrews (Chapman Hall and Co.); "Theory of Structures," Professor Morley.

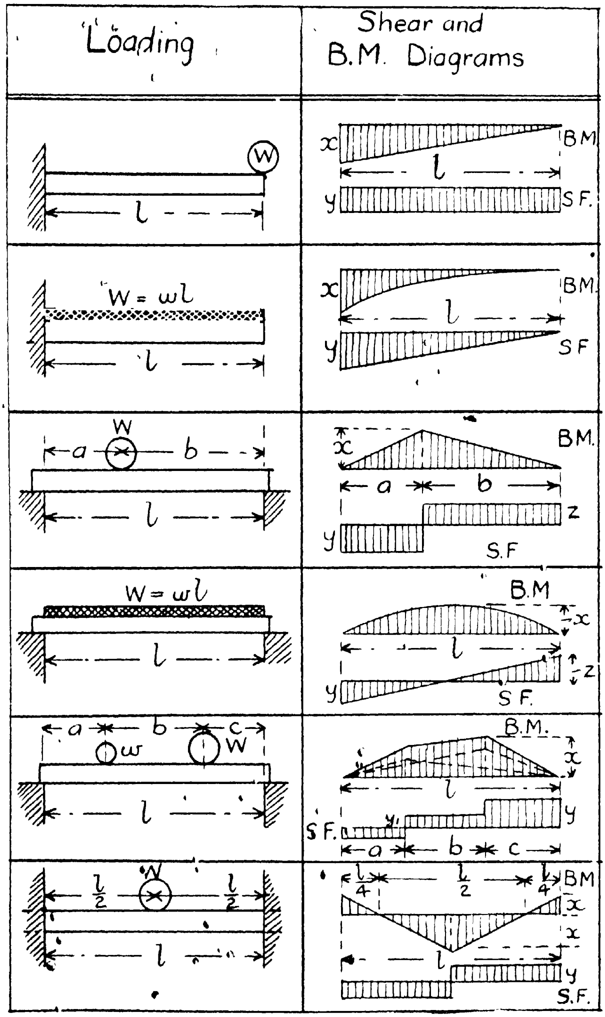

Loading
Shear and B.M. Diagrams
W
l
x
BM
y
S F.
W = wl
l
x
BM
y
SF
W
a
b
l
x
BM.
a
b
z
y
S.F
W = wl
l
B.M
x
l
z
y
S F.
a
b
c
w
W
l
B.M.
x
l
y
S F.
y
a
b
c
W
l/2
l/2
l
l/4
l/2
l/4
BM
x
x
l
y
S.F.

FIG. 12.

TABLE VI.

Maximum Bending Moment.	*Maximum Shearing Force.*	*Maximum Deflection.*
$x = \mathrm{W}l$	$y = \mathrm{W}$	$\frac{\mathrm{W}l^3}{3\mathrm{EI}}$ at W
$x = \frac{wl^2}{2}$ $= \frac{\mathrm{W}l}{2}$	$y = wl$ $= \mathrm{W}$	$\frac{wl^4}{8\mathrm{EI}}$ or $\frac{\mathrm{W}l^3}{8\mathrm{EI}}$ at W.
$x = \frac{\mathrm{W} \cdot ab}{l}$	$y = \frac{\mathrm{W}b}{l}$ $z = \frac{\mathrm{W}a}{l}$	$\frac{\mathrm{W}a^2b^2}{3\mathrm{EI}(a+b)}$
$x = \frac{\mathrm{W}l}{8}$ $= \frac{wl^2}{8}$	$y = z = \frac{\mathrm{W}}{2}$ $= \frac{wl}{2}$	$\frac{5\mathrm{W}l^3}{384\mathrm{EI}}$ or $\frac{5wl^4}{384\mathrm{EI}}$
$x = \frac{ac^2}{l}(\mathrm{W}+w)$ $+ \mathrm{W} \cdot \frac{bc^2}{l}$	$y = \frac{ac}{l}(\mathrm{W}+w)$ $+ \mathrm{W} \cdot \frac{bc}{l}$	—
$x = \frac{\mathrm{W}l}{[illegible]}$	$y = \frac{\mathrm{W}}{2}$	$\frac{wl^4}{384\mathrm{EI}}$ or $\frac{\mathrm{W}l^3}{384\mathrm{EI}}$

under tensile action. There will evidently be one layer, situated near the centre of the beam, which neither extends nor compresses.

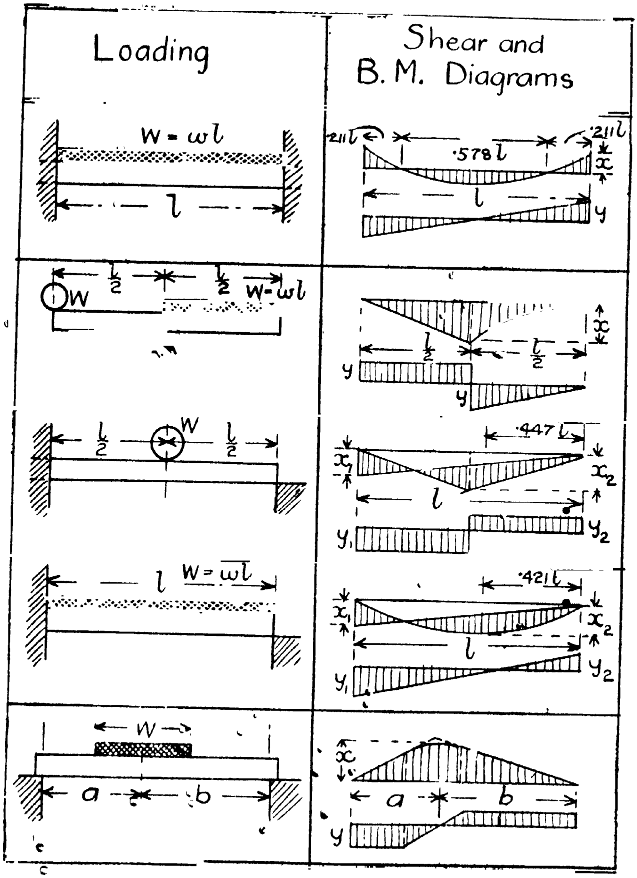


Fig. 13.

The axis of the section at which this effect occurs is termed the *Neutral Axis*, and the layer concerned the *Neutral Layer*.

An important property of the neutral axis is that it always passes through the centre of gravity of the section.

Consider next the two equivalent forces acting upon any section xy of the beam. If the beam be supposed cut at this section the dispositions of the forces preserving balance

TABLE VII.

Maximum Bending Moment.	*Maximum Shearing Force.*	*Maximum Deflection.*
$x=\frac{wl^2}{12}$ $=\frac{Wl}{12}$	$y=\frac{W}{2}$	$\frac{Wl^3}{192EI}$
$x=Wl$	$y=W$	$\frac{Wl^3}{3EI}$ at centre
$x_1=\frac{3Wl}{16}$ $x_2=\frac{Wl}{4}$	$y_1=\frac{11W}{16}$ $y_2=\frac{5W}{16}$	$\frac{Wl^3}{107EI}$ at $0{\cdot}447l$
$x_1=\frac{Wl}{8}$ $x_2=\frac{Wl}{8}$	$y_1=\frac{5W}{8}$ $y_2=\frac{3W}{8}$	$\frac{Wl^3}{185EI}$ at $0{\cdot}421l$
$W\cdot\frac{ab}{a+b}-\frac{Wc}{4}$	$W\cdot\frac{b}{a+b}$	$\frac{Wa^2b^2}{3EI(a+b)}-\frac{Wc^3}{8EI}$

will be readily seen to be those shown in Fig. 14 (B), and to comprise—

(1) A compressive force above the neutral axis, C.

(2) A tensile force below the neutral axis, F.

(3) A vertical shear force, S.

The moment of the couple due to the forces C and F is called the moment of resistance of the stresses acting, or of the section, and the following relation holds:

$$\left.\begin{array}{c}\text{Moment of resistance}\\ \text{of the section}\end{array}\right\} = \text{External B.M. at the section.}$$

The Engineer's Beam Theory.

It has been assumed that there are two equivalent tensile and compressive forces, F and C respectively, which resist the external B.M. due to the loading of beam. Actually,

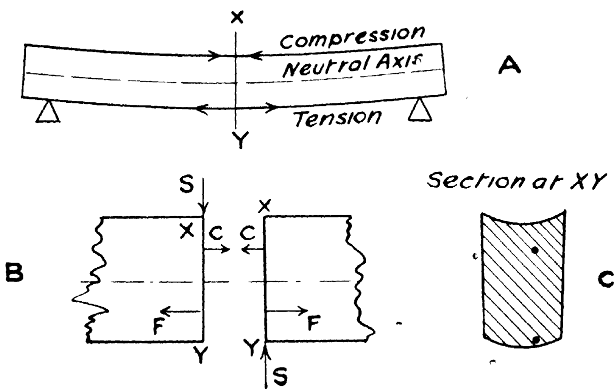


FIG. 14.—STRESSES IN LOADED BEAMS.

however, there is a distributed stress over each part of the cross-section of the beam, the stress being tensile below, and compressive above. Moreover, the distribution of stress is such that it is zero at the neutral axis, and increases to maximum values at the furthermost parts of the section.

A very valuable, yet simple, theory, the results of which are widely employed in engineering design practice, is based upon the following assumptions—viz.:

1. That the material of the beam is perfectly elastic both in tension and in compression—that is to say, it

follows Hooke's Law*—and also it has the same value of Young's Modulus (E) for both tension and compression.

2. That a cross-section of the beam, which is plane before, is also plane after bending.
3. That the limit of elasticity (or Elastic Limit) is not exceeded by any of the stresses. A certain amount of criticism has been based upon the failure of the engineer's beam theory to predict "breaking loads" and phenomena beyond the Elastic Limit; this is, of course, incorrect, as the assumptions upon which the theory is based apply only within the Elastic Limit.
4. That every longitudinal layer is free to contract or extend under stress, either laterally or longitudinally, just as it the layers were separate.
5. That the initial radius of curvature of the beam is very large compared with the dimensions of any cross-section.

One of the first consequences of these assumptions, more particularly of (1) and (2), is that the distribution of stress across the section obeys a linear law of variation—that is to say, it varies directly as the distance from the neutral axis. Thus, if p = the stress (tensile or compressive) at any distance y from the neutral axis, then—

$$p = k \cdot y,$$

where k is a constant depending upon the value of the B.M. and of the shape of the section. The value of the stress p at any given distance from the neutral axis will vary directly as the B.M., and inversely as the moment of inertia of the section.

It is not proposed to give analytical proofs of these formulæ here, owing to the limited scope and the nature of the chapter, but rather to confine attention to results obtained by their use.

* *Vide* p. 8.

Stresses across the Section of a Beam.

The following formula, then, holds, under the given assumptions—

$$p = y \cdot \frac{M}{I},$$

where p = the stress at distance y from the neutral axis,
M = B.M. at the section,
I = Moment of Inertia of the section about the neutral axis.

Units Employed:

If M be expressed in *pounds inches*, I in (inches)^4, and y in *inches*, then the stress p will be in pounds per square inch.

If M be expressed in kilogramme centimetres, and I and y in centimetre units, then p will be the stress in kilogrammes per square centimetre.

It will be seen that the value of the stress occurring depends largely upon the shape of the section, and that sections having a large moment of inertia about the neutral axis will have smaller stresses for a given depth and B.M. Values of the moments of inertia for the sections shown in Fig. 15 are given in Table VIII.

Economical Sections:

From the point of view of material economy (which is an important one, from the automobile and aircraft points of view), it is desirable to design beam sections so that their moments of inertia, for a given depth, are as large as possible. This is effected by massing the material as far away as possible from the neutral axis.

The ratio $\frac{I}{y}$ is termed the *Strength Modulus** of the section, and it is a measure of the moment of resistance which the material of the section offers to bending—

$$\text{for } M = p \cdot \frac{I}{y}.$$

* Sometimes denoted by the symbol *Z*.

Special Cases:

1. In the case of a square beam section of side a—

$$I=\frac{a^4}{12} \text{ and } y=\frac{a}{2}, \text{ so that } \frac{I}{y}=\frac{a^3}{6}.$$

2. For a rectangle of breadth b and depth d—

$$I=\frac{bd^3}{12} \text{ and } y=\frac{d}{2}, \text{ so that } \frac{I}{y}=\frac{bd^2}{6}.$$

3. For a square of side a with diagonal along neutral axis—

$$I=\frac{a^4}{12} \text{ and } y=\frac{a}{\sqrt{2}}, \text{ so that } \frac{I}{y}=\frac{a^3}{6\sqrt{2}} \text{ or } \frac{a^3\sqrt{2}}{12}.$$

4. For a circular section of diameter d—

$$I=\frac{\pi d^4}{64} \text{ and } y=\frac{d}{2}, \text{ so that } \frac{I}{y}=\frac{\pi d^3}{32}.$$

TABLE VIII.

MOMENTS OF INERTIA OF SOLIDS.

Type of Body.	*Moment of Inertia.*	*Radius of Gyration.*
Circular disc about perpendicular central axis. Mass $=$ M, radius $=r$	$\frac{Mr^2}{2}$	$\frac{r}{\sqrt{2}}$
Elliptical disc about perpendicular central axis. Mass $=$ M, major axis $=a$, minor axis $=b$	$M\frac{a^2+b^2}{2}$	$\frac{\sqrt{a^2+b^2}}{\sqrt{2}}$
Sphere about a diameter	$\frac{2}{5}Ma^2$	$a\sqrt{\frac{2}{5}}$
Rod of length l about perpendicular axis through centre	$\frac{Ml^2}{12}$	$\frac{l}{\sqrt{12}}$
Rod of length l about perpendicular axis through end	$\frac{Ml^2}{3}$	$\frac{l}{\sqrt{3}}$
Cylinder about perpendicular axis. Radius $=r$	$\frac{Mr^2}{2}$	$\frac{r}{\sqrt{2}}$
Cone about axis perpendicular to its height l through apex	$\frac{Ml^2}{3}$	$\frac{l}{\sqrt{3}}$

PROPERTIES OF SECTIONS.

No.	*Moment of Inertia about Dotted Axis through C.G.*	*Radius of Gyration* $=\sqrt{\frac{I}{A}}$.	*Strength Modulus* Z.
1	$\frac{bd^3}{12}$	$0{\cdot}289d$	$\frac{bd^2}{6}$
2	$\frac{d^3[b^2+4bb^1+b_1^2]}{36(b+b^1)}$ $a=\frac{d}{3}\left[\frac{b+2b_1}{b+b_1}\right]$	$d\sqrt{\frac{b^2+4bb_1+b_1^2}{18(b+b_1)(2b_1+b)}}$	$\frac{d^2[b^2+4bb^1+b_1^2]}{18(b+b^1)}$
3	$\frac{bd^3}{36}\ a=\frac{d}{3}$	$0{\cdot}2357d$	$\frac{bd^2}{18}$
4	$\frac{5\sqrt{3}}{16}a^4$	$0{\cdot}456a$	$\frac{5a^3}{8}$
5	$\frac{a^4}{12}$	$0{\cdot}289a$	$\frac{a^3\sqrt{2}}{12}$
6	$\frac{1}{2}[b(a_1^2-f^2)+b_1(f^3+a^3{}_2)]$ $a_1=\frac{bb_2^2+b_1d_1(d+b_3)}{2[bd-(b-b_1)d_1]}$	—	$\frac{I}{d_1}$ and $\frac{I}{d_1-f}$
7	$\frac{bd^3-(b-b_1)d_1^3}{12}$ where $d=2a+d_1$	$\sqrt{\frac{bd^2-(b-b_1)d_1^2}{12[bd-(b-b_1)d_1]}}$	$\frac{bd^3-(b-b_1)d_1^3}{6d}$
8*	$\frac{\pi}{64}d^4$	$0{\cdot}25d$	$\frac{\pi d^3}{32}$
9 Ellipse	$\frac{\pi}{64}bd^3$	$0{\cdot}25d$	$\frac{\pi bd^2}{32}$
10	$\frac{d^4}{16}\left[\frac{\pi}{8}-\frac{8}{9\pi}\right]$ $=0{\cdot}0069d^4$ $a=\frac{2d}{3\pi}=0{\cdot}2122d$	$0{\cdot}132d$	$\frac{I}{a}$ and $\frac{I}{\frac{d}{2}-a}$
11 Parabola	$\frac{8}{175}bh^3$	$0{\cdot}2619h$	—

* For an annular circular section for which outside diameter $=d$ and inside diameter $=d_1$;

$$I=\frac{\pi}{64}[d^4-d_1^4] \text{ and } Z=\frac{\pi}{32}\left[\frac{d^4-d_1^4}{d}\right].$$

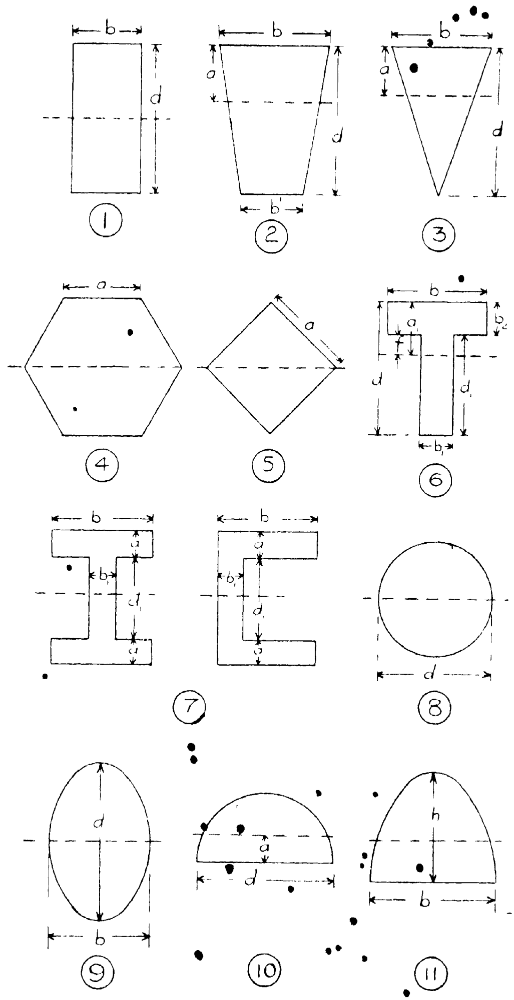


FIG. 15.—MOMENTS OF INERTIA OF AREAS

5. For a thin hollow circular section of diameter d and area A—

$$I = \frac{A \cdot d^2}{8} \text{ and } y = \frac{d}{2}, \text{ so that } \frac{I}{y} = \frac{Ad}{4}.$$

The relative strength moduli of beams of equal area having the sections given in (1), (2), (3), and (4), will be (calling the area unity in each case) as—

$$\tfrac{1}{6} : \frac{\sqrt{2}}{6} : \frac{\sqrt{2}}{12} : \frac{1}{4\sqrt{\pi}},$$

or as—

$$1{\cdot}176 : 1{\cdot}662 : 0{\cdot}831 : 1{\cdot}000.$$

Shear Stress in Beams.

Hitherto, the normal tensile and compressive stresses (due to bending) only have been considered in detail, although it has been shown* that a vertical shear stress must exist along any section.

This shear stress must be accompanied by an equal shear stress acting at right angles to it—that is, along the length of the beam.

Now the shear stress, as in the case of the normal stresses, is not uniform over any section; it can be shown, by analytical methods, to vary across the section, according to the shape of the section, being a maximum at the neutral axis, and a minimum at the outermost parts of the section.

The value of the horizontal (and also the accompanying vertical) shear stress at any distance from the neutral axis, is given by—

$$q = \frac{S \cdot A \cdot y_0}{b \cdot I},$$

where S = total shear stress on the section due to bending,

A = area between the point of section at which q is considered and the outermost part of section. (This area is shown shaded in Fig. 16.)

y_0 is the distance of the C.G. of this area from the neutral

* *Vide* p. 20.

axis, b = the breadth of section, and I = its moment of inertia about the neutral axis.

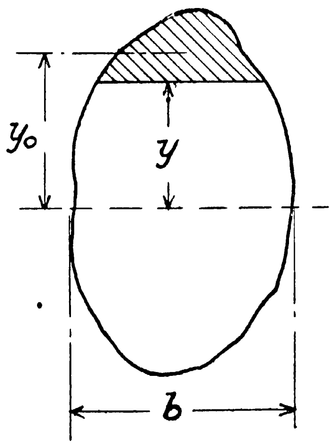


FIG. 16.

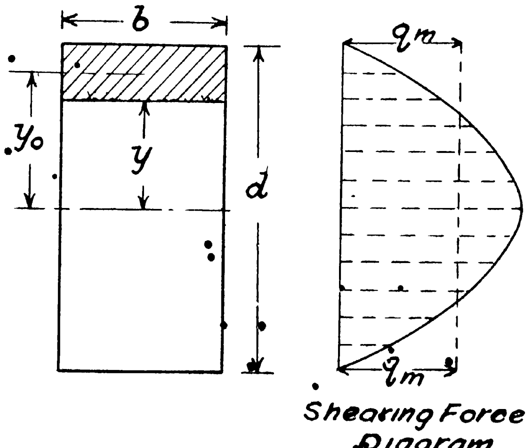


FIG. 17.—SHEAR STRESS OVER RECTANGULAR BEAM SECTION.

Consider the case of a rectangular section as shown in Fig. 17. The shearing stress q at any plane situated at a distance y from the neutral axis is given by—

$$q = \frac{6S\left(\frac{d^2}{4} - y^2\right)}{bd^3}.$$

At the neutral axis $y = 0$ and $q = \frac{3}{2} \cdot \frac{S}{bd}$.

At the outermost layer $y = \frac{d}{2}$ and $q = 0$. The intensity of shear stress variation for a rectangular section of the proportions shown in Fig. 17 is illustrated in the diagram on the right-hand side.

For a circular section the maximum shear stress, at the neutral axis, is $\frac{4}{3}$ of the mean.

I-Beam Sections.

The distribution of shear stress, over the section of an **I** beam, of the proportions shown in Fig. 18, is illustrated in the scale diagram on the right-hand side.

Employing the previous notation and that of the diagram, the intensity of shear stress in the flange, at a distance y from the neutral axis, is given by—

$$q = \frac{S}{2I}\left(\frac{D^2}{4} - y^2\right).$$

At the inner edge of the flange $y = \frac{d}{2}$ and then—

$$q = \frac{S}{2I}\left(\frac{D^2}{4} - \frac{d^2}{4}\right).$$

For the web, if y_1 be the distance from the neutral axis, the intensity of shear stress—

$$q = \frac{S}{8I}\left[\frac{B}{b}(D^2 - d^2) + d^2 - 4y^2\right].$$

At the centre $y = 0$, and—

$$q = \frac{S}{8I}\left[\frac{B}{b}(D^2 - d^2) + d^2\right].$$

At the inner edge of the flange (where the web ends)—

$$y = \frac{d}{2} \text{ and } q = \frac{S}{8I} \cdot \frac{B}{b} \cdot (D^2 - d^2).$$

It will be observed that the shear stress changes at this place by an amount equal to $\frac{B}{b}$ times its value for the flange. It will also be seen that the intensity of shear stress is nearly uniform over the web, and is considerably greater than in the flanges.

For most practical purposes it is sufficiently accurate to assume that the web takes all of the shearing force due to bending, and that the flanges take all of the normal stresses due to the bending moment.

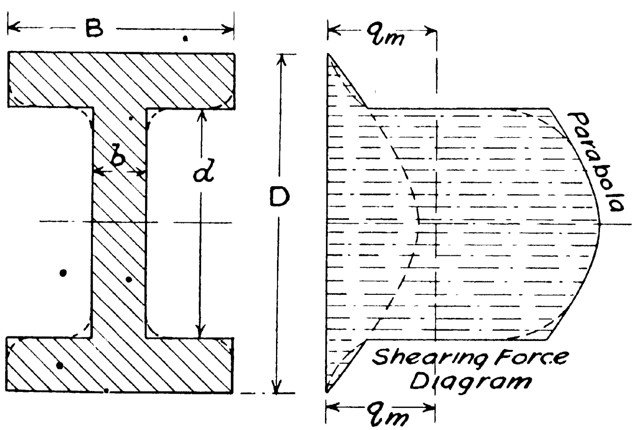


FIG. 18.—SHEAR STRESS OVER I-BEAM SECTION.

It should be remembered that the vertical shear stress at any place is accompanied by an equal horizontal shear stress at the same place.

This horizontal stress must be taken into account in the case of built-up, glued, riveted, or jointed beams, for the rivets, glue, or joint materials have to withstand this shearing stress. This point is often overlooked in design work, frequently with serious consequences. The effect of rounding the corners of the I beam, upon the shear-intensity diagram, is shown by the dotted lines in Fig. 18.

Web and Flange Stresses.

For the simple I-beam section shown in Fig. 19, and with the notation indicated thereon, the moment of resistance may at once be computed.

Assuming that the web takes none of the normal stresses owing to its relatively small area compared with the flanges, and denoting the mean tensile and compressive stresses upon the upper and lower flanges by f_t and f_c respectively, then—

$$\text{Moment of Resistance} = A_T f_t \cdot h = A_c \cdot f_c \cdot h.$$
$$= \text{B.M. at the section.}$$

$$\text{So that } \frac{A_T}{A_c} = \frac{f_c}{f_t},$$

where A_T and A_c are the respective areas of the flanges.

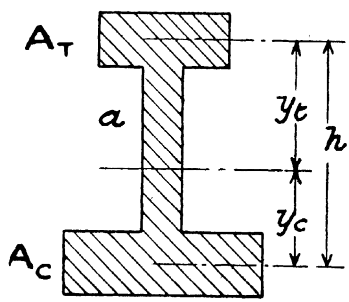


FIG. 19.

The areas of the flanges are therefore inversely proportional to the stresses to which they are subjected.

The safe shearing stress $q = \frac{S}{a}$,

where S = total S.F. on section,
a = area of web.

It is usually found in practice that the area a given by this method gives a much thinner web than can be actually employed. The size of the web is then governed by local buckling conditions.

If the web has an appreciable area compared with the

flanges, as in the case of cast-iron beams, and aeroplane wing spars, then the following relations hold:

$$y_c = \frac{f_c}{f_c+f_t} \cdot h.$$

$$y_t = \frac{f_t}{f_c+f_t} \cdot h.$$

$$A_c = A_t \cdot \frac{f_t}{f_c} + a \cdot \frac{f_t - f_c}{2f_c}.$$

$$A_T = A_c \cdot \frac{f_c}{f_t} + a \cdot \frac{f_c - f_t}{2f_t}.$$

The values of the strength moduli are given by—

$$Z_c = h\left[A_c + \left(2 - \frac{f_t}{f_c}\right) \cdot \frac{a}{6}\right] \text{ for compression,}$$

and—

$$Z_t = h\left[A_t + \left(2 - \frac{f_c}{f_t}\right) \cdot \frac{a}{6}\right] \text{ for tension.}$$

The moment of resistance, or B.M., $= f_c \cdot Z_c = f_t \cdot Z_t$. In the case of thin flanges, liable to local or secondary buckling stresses, under compression, it is usual to take a value of f_c at from 50 to 80 per cent. of the value given by crushing tests of short specimens. In the case of beams with thin webs, which, however, are sufficiently strong to take the shear, it is usual to locally stiffen same, by means of suitable webs, side-members, etc.

Some typical examples of economical solid and built-up beam sections, as employed in practice, are shown in Fig. 20.

The Resultant Stress in Beams.

The shear and normal stresses in beams under load have each been considered separately, and it now remains to study the combined effect at each part of the section of these stresses.

The stresses which occur at any part of the section are those shown in Fig. 14, and consist of—

1. A normal stress, either tensile or compressive.
2. A shear stress acting horizontally.
3. An equal shear stress acting vertically.

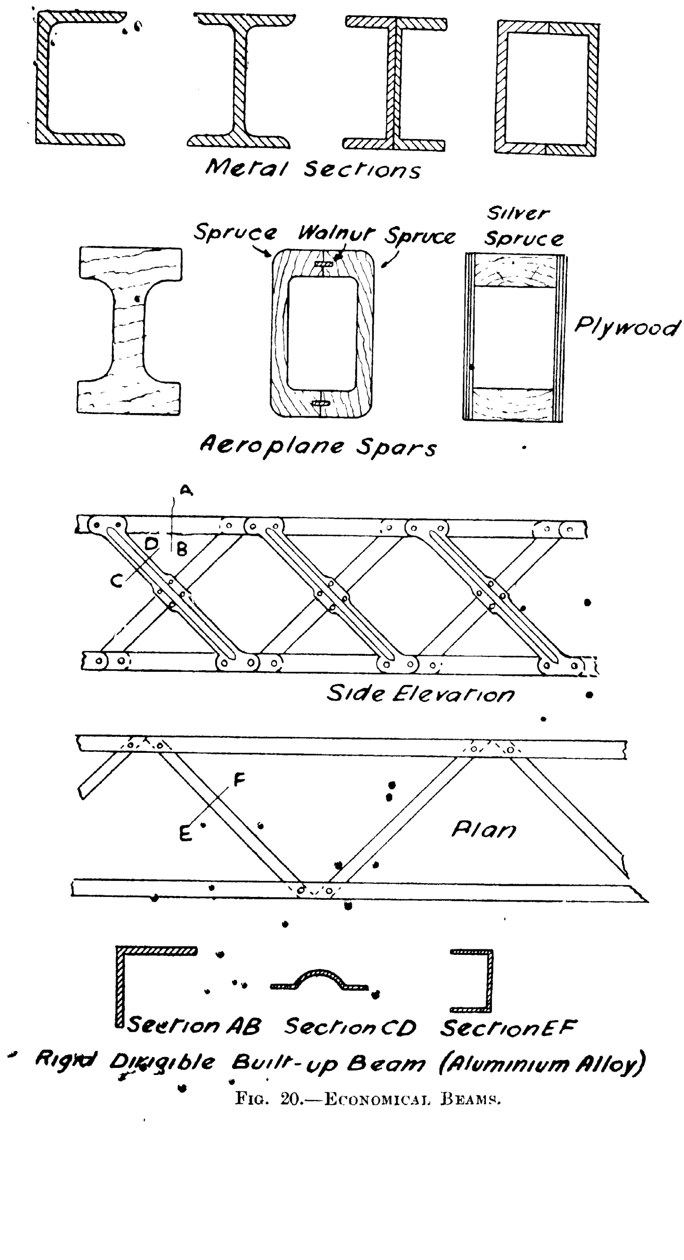


FIG. 20.—ECONOMICAL BEAMS.

The resultant or principal stress corresponding to these stresses acts normally to a plane,* the inclination of which depends upon the relative values of the component stresses —that is, to the locality of the part of the section at which they are considered.

Fig. 21 illustrates the manner in which the principal stresses occur over the section of a beam, the right-hand diagram showing the resultant of the stresses shown in the other two diagrams.

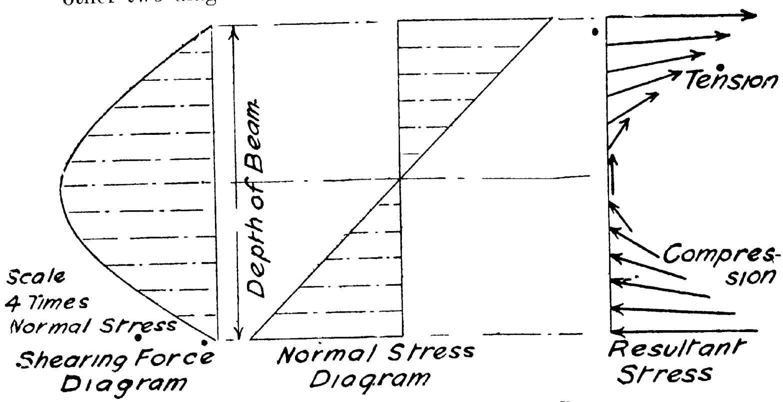


FIG. 21.—THE RESULTANT STRESSES IN A BEAM.

If a number of such sections be treated in this way, a series of curves, showing the directions of the principal stresses, can be obtained, similar to that shown in Fig. 21A. The concave-upwards curves marked positive are compression stress directions, whilst the concave-downwards curves marked negative are tensile; the example shown corresponds with the case of a uniformly loaded beam supported at its ends. Fig. 21B shows the manner in which the shear and normal stresses vary along the span of a loaded beam supported at its ends.

It will be observed that the shear stress diagram vanishes at the centre section of the beam, whilst the normal stress reaches its maximum values, whereas at the ends of the

* *Vide* p. 20.

beam the shear stress is a maximum and the normal stresses zero. The effect upon the directions of the principal stresses is clearly shown in the diagram.

Deflection of Beams.

Having considered the stresses occurring in loaded beams, it now remains to study the effect of the strains produced.

Upon the same assumptions that were made in the case of the stresses, as regards stressing within the elastic limit and in connection with plane sections remaining plane after

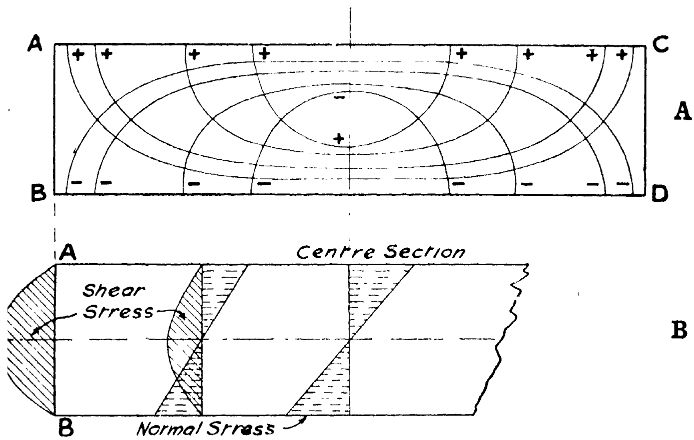


FIG. 21A.—A, LINES OF PRINCIPAL STRESSES IN LOADED BEAM; B, DISTRIBUTION OF SHEAR AND NORMAL STRESSES.

bending, it can be shown that the curvature* produced by bending is proportional to the bending moment and inversely to the moment of inertia, and to the modulus of elasticity—that is:

$$\frac{1}{R}=\frac{M}{EI},$$

where R = radius of curvature,
E = Young's modulus,
I = Moment of inertia about neutral axis,
M = Bending moment

* Here "curvature" is used in the sense that it is inversely proportional to the radius of curvature.

But it has been shown that

$$\frac{M}{I} = \frac{p}{y},$$

so that—

$$\frac{1}{R} = \frac{M}{EI} = \frac{p}{Ey}.$$

It follows from this that if the B.M. is constant for all places along the beam, then the beam will be bent uniformly to a circular arc.

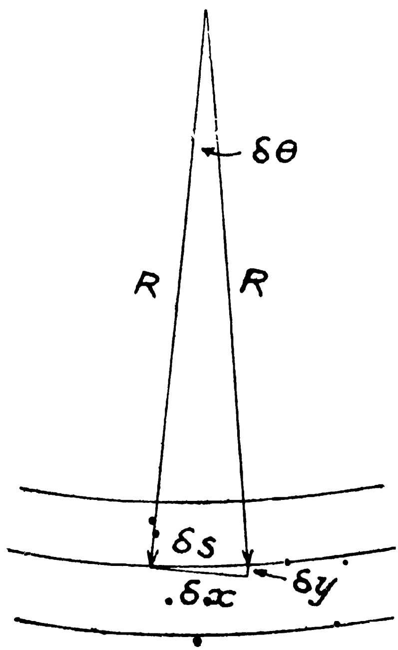


FIG. 22.

Mathematical Expression for Curvature, Slope, and Deflection.

If distances along the span (Fig. 22) from a given origin be denoted by x, deflections at x, perpendicular to the initial length of the beam, by u, and the angular slopes at x of the beam by θ, then the following relations hold:

I.

$$\frac{1}{R} = \frac{M}{EI} = \frac{d\theta}{dx}.$$

so that—

$$\theta = \frac{du}{dx},$$

and—

$$\theta = \int \frac{1}{R} \cdot dx \cdot = \int \frac{M}{EI} \cdot dx,$$

$$u = \int \theta \cdot dx = \iint \frac{M}{EI} \cdot dx.$$

It is usual to choose the origin at the point of loading or of support, and to express M, the bending moment, in terms of the distance x and the loads.

Example.—Find the slopes and deflections at the centre and ends of an uniformly loaded beam supported at the ends.

Let w = the uniform load per foot run of beam;
l = span of beam.

Taking the origin at the centre, the B.M. at any point situated at a distance x from the origin is given by—

$$M = \frac{wl^2}{8} - \frac{wx^2}{2}.$$

The slope—

$$\theta_x = \int \frac{1}{R} dx = \int \frac{M}{EI} dx = \int \frac{w}{2EI}\left(\frac{l^2}{4} - x^2\right) dx = \frac{wx}{2EI}\left(\frac{l^2}{4} - \frac{x^2}{3}\right).$$

At the centre $x = 0$, and there is no change of slope. At the ends $x = \frac{l}{2}$ and $\theta = \frac{wl^3}{24EI}$.

(It should be noted that if w is in pounds, E in pounds per square inch, and l and I are in inch units, the slope θ is given in circular measure, or radians, 1 radian being equal to 57·296°.)

The deflection—

$$u_x = \int \theta \cdot dx = \frac{w}{2EI} \int \left(\frac{l^2 x}{4} - \frac{x^3}{3}\right) dx = \frac{wx^2}{8EI} \cdot \left(\frac{l^2}{2} - \frac{x^2}{3}\right).$$

At the centre, the deflection will be given by putting $x = \frac{l}{2}$, since the origin is there. Then—

$$u = \frac{5}{384} \cdot \frac{wl^4}{EI}.$$

Similarly for other types of loading.

Special Cases of Loaded Beams.

It can be shown that the greatest slope of any loaded beam can be expressed in the form—

$$\theta_m = a \cdot \frac{Wl^2}{EI};$$

and the greatest deflection by—

$$u_m = b \cdot \frac{Wl^3}{EI},$$

where a and b are constants, W the total load, and l the span.

TABLE IX.

VALUES OF CONSTANTS IN SLOPE AND DEFLECTION FORMULÆ.

Type of Beam.	*Loading.*	*Value of Constant.* Slope. a. In $\theta_m = a \cdot \frac{wl^2}{EI}$.	*Value of Constant.* Deflection. b. In $u_m = b \cdot \frac{wl^3}{EI}$.
Cantilever of uniform section.	Single load at end.	$\frac{1}{2}$	$\frac{1}{3}$
Cantilever of uniform section.	Uniformly distributed load.	$\frac{1}{6}$	$\frac{1}{8}$
Beam of uniform section supported at ends.	Single load at centre.	$\frac{1}{16}$	$\frac{1}{48}$
Beam of uniform section supported at ends.	Uniformly distributed load.	$\frac{1}{24}$	$\frac{5}{384}$

The deflections of a beam subjected to more than one load is equal to the algebraical sum of the deflections due to the separate loads.

Shape of Bent Beam (Transverse Bending).

When an initially straight beam is bent, the longitudinal filaments on the compression side of the neutral axis become "bulged," whilst the tension side filaments become contracted, with the net result that an originally rectangular

section approximately assumes the shape shown in Fig. 14, for the case of a beam supported at the ends.

Since the lateral strain $= \sigma$ (longitudinal strain), where σ is Poisson's ratio, it follows that the transverse radius of curvature will be σ times the longitudinal radius, or $R\sigma$.

In practice, the assumption of freely extending or contracting filaments does not hold for most materials, and for wide beams, such as flat strips.

Work Done in Bending a Beam.

The resilience of a beam is measured by the sum of one-half of the products of the B M.'s and the angular slopes according to the relation—

$$E = \int \tfrac{1}{2} M \cdot d\theta = \frac{1}{2EI} \int M^2 \cdot dx,$$

or to the sum of one-half of the products of the loads into the deflections caused by the loads.

$$E = \int \tfrac{1}{2} w \cdot du.$$

It can be shown that in the case of a rectangular beam of constant section, subjected to a uniform B M.—

$$E = \frac{f_c^2 V}{6E},$$

where f_c = maximum stress at the outermost fibre,
V = volume of beam.

Stresses due to Torsion.

When a pair of equal, but opposite, couples are applied to the ends of a rod or shaft, and which act about the axis of the shaft, the stress caused is one of pure shear, and the shaft is said to be subjected to *torsion*, the moment of the couple being termed the *torque*.

The intensity of the shear stress, in the case of a circular shaft, varies from zero at the centre to a maximum at the periphery, the distribution being that shown in Fig. 23 (*c*).

The shear strains caused will also follow the same law of distribution.

The shear stress q_x at any radius x will be given by—

$$q_x = \frac{q_r}{r} \cdot x,$$

where q_r = shear stress at radius r.

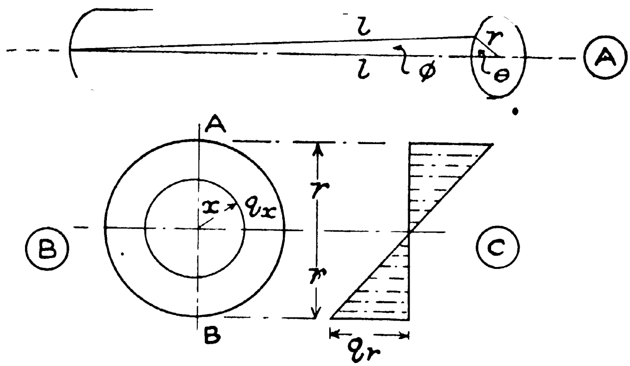


FIG. 23.

The shear strain ϕ at radius x (or angle of shear) is given by—

$$q_x = C \cdot \phi.$$

If T = the applied torque, then—

$$T = \frac{\pi q_r \cdot r^3}{2} = \frac{\pi q_r d^3}{16},$$

where $d = 2r$ = the diameter of the shaft.

For a *hollow shaft* of external and internal diameters d and d_1 respectively, the maximum shear stress q at the periphery is given by—

$$T = \frac{\pi q}{16} \cdot \frac{d^4 - d_1^4}{d};$$

$$i.e., \ q = \frac{16 T \cdot d}{\pi [d^4 - d_1^4]}.$$

The maximum intensity of stress is altered very little by removing quite an appreciable amount of material from around the centre. Thus the relative values of the maximum stresses, for a given torque, in the cases of a solid

shaft, and a hollow shaft of the same outside diameter, but with the inside diameter equal to half of that of the outside, are as 15 to 16 respectively.

The relative weights are as 4 to 3, and the relative ratios $\frac{\text{maximum shear stress}}{\text{weight}}$ are as 3·75 to 5·$\dot{3}$, so that the hollow shaft is considerably the stronger for its weight.

Angle of Twist.

The angle of twist θ for a length l of shaft, of diameter d, is given by—

$$\theta \cdot \frac{d}{2} = \phi \cdot l \text{ (where } \phi = \text{longitudinal twist)}$$

$$= \frac{q}{C} \cdot l.$$

$$\text{Whence } \theta = \frac{32T \cdot l}{\pi d^4 C}.$$

For a hollow shaft of external diameters d and d_1 respectively—

$$\theta = \frac{32Tld}{\pi C[d^4 - d_1^4]}.$$

Note.—The angles θ and ϕ are given in radians.

Units.—If linear dimensions such as l, d, d_1, etc., be in inches, T in pounds inches, C in pounds per square inch, then the shear stresses, such as q, will be in pounds per square inch.

Horse-Power Transmitted by Shafting.

The preceding results may be applied to practical engineering cases for ascertaining the dimensions of shafting or members transmitting torque, or power.

In order to determine the diameter (d inches) of the solid shaft which will transmit a given horse-power (H.P.), it is necessary to know: (1) the revolutions per minute (N); (2) the material of the shaft; and (3) the permissible factor of safety.

The higher the revolutions, for a given H.P., the smaller will be the torque, and therefore the diameter of the shaft.

$$\text{H.P.} = \frac{\text{Torque (pounds inches)} \times N}{63030}$$

Factors (2) and (3) determine the value of the shear stress q. Materials possessing a high ultimate tensile strength will require smaller diameters, and if the torque is a fluctuating one, or is applied frequently and suddenly, the factor of safety will be higher than for steady torques; it is always the maximum value of the torque which should be considered in such cases.

The diameter d is given by—

$$d = 68{\cdot}5\sqrt{\frac{\text{H.P.}}{\text{N}\cdot q}} \text{ inches,}$$

q = the greatest permissible shear stress in pounds square inch.

For steady torques $q = 9000$ pounds square inch for *wrought iron,* 4500 for *cast iron,* 10,500 for *mild steel,* 13,500 for *cast steel,* 19,000 for *untreated nickel-chrome steel,* and 33,000 for *air-hardened nickel chrome steel.*

For varying torques, much lower values of q must be taken.*

ombined Bending and Torsion.

Many examples occur in aeronautical and automobile work of shafts which are subject to a bending action in addition to that of torsion. For example, any overhung shaft transmitting power by torsion will be under bending action due to the weight of the overhung part or connecting-rod thrust. The crank-shaft of an engine is subjected to the bending action of the connecting-rod thrust, and to the torsion of the crank. Another common example is that of a shaft having a pulley, the belt on which exerts a pull upon the shaft whilst running. If the bending moment is appreciable compared with the torque, its effect should always be taken into account. Moreover, the maximum values of these quantities should be considered, and not the mean values, for in many cases, notably those occurring in petrol engine work, the torque varies, sometimes considerably during a working cycle.

The following table gives the ratios of the maximum to

* See p. 56.

mean values of the torque upon the crank-shaft in the case of different types of petrol engine. The bore and stroke in each case are 3 and 4 inches respectively, and the constant speed 1000 R.P.M. The ratio of connecting rod to crank is 4·0.

TABLE X.

PETROL ENGINE TORQUES.

Type of Engine.	*Maximum Torque Value.*	*Ratio* $\frac{\textit{Maximum Torque}}{\textit{Mean Torque}}$.
	Pounds Feet.	
Single-cylinder	204	8·6
Two-cylinder vertical. (Cranks at 180°.)	204	4·0
Two-cylinder opposed type. (Cranks at 180°.)	204	3·9
Two-cylinder 90° **V** type. (Single crank.)	204	4·0
Four-cylinder vertical. (Cranks at 0°, 180°, 180°, 0°– ordinary motor-car type.)	204	2·0
Six-cylinder vertical (Cranks at 0°, 120°, 240°, 240°, 120°, 0°– ordinary motor-car type.)	204	1·4

When a shaft is under combined bending and twisting action, there will be at any cross-section a direct tensile or compressive stress varying from zero value at the neutral axis to a maximum at the furthermost parts of the section or periphery, and a shear stress varying from zero at the centre to a maximum at the periphery.

The intensity of the normal stress on the surface is given by—

$$p = \frac{32M}{\pi d^3},$$

and of the shear stress at the same place by—

$$q = \frac{16T}{\pi d^3}.$$

These stresses occur in different directions, and further

there is another accompanying shear stress q acting at right angles to the one above mentioned.

These stresses may be combined by the methods already considered, and the principal stress values r will be found to be given by—

$$r = \frac{p}{2} \pm \sqrt{q^2 + \frac{p^2}{4}}$$

$$= \frac{16}{\pi d^3}\left[M \pm \sqrt{T^2 + M^2}\right].$$

The resultant stress r will be seen to be similar to that caused by a *single equivalent bending moment* of value $\frac{1}{2}\left[M \pm \sqrt{T^2 + M^2}\right]$ or by a single *equivalent twisting moment* of amount $\left[M \pm \sqrt{T^2 + M^2}\right]$. The resultant stress r is, however, a *normal* stress, the positive root value corresponding to the maximum, and the negative root value to the minimum principal stress, which occurs at right angles to the direction of the former.

The greatest shear stress due to p and q acting together is given by—

$$q_m = \sqrt{q^2 + \frac{p^2}{4}} = \frac{16}{\pi d^3}\sqrt{M^2 + T^2},$$

and occurs over planes inclined at 45° to the planes of principal stress.

The maximum principal stress value is usually considered as being the working stress in the shaft, whilst the maximum shear stress determines the manner of failure, when the shaft is loaded to destruction.

Work Done in Torsion.

The mean resilience of a shaft under torsion is given by—

$$w = \frac{1}{2}\,T\,\frac{\theta}{l}$$

$$= \frac{q^2 \pi d^2}{16C} \text{ per unit length.}$$

Or mean resilience per unit volume $= \frac{q^2}{4C}$, where q is the shear stress at the circumference.

Struts and Columns.

Although this subject is chiefly experimental, yet many of the formulæ for expressing the strength of struts are based upon theoretical considerations, and will therefore be considered in the present chapter.

When a short column* is compressed, the crushing strength is well defined in brittle materials, such as cast iron and timbers, but is not so evident in the case of ductile materials, like mild steel, owing to the lateral yielding or flow of the metal.

When the length of the column or strut is at least two times the least cross-sectional dimension, and above, the column fails in quite a different manner under end-loading;

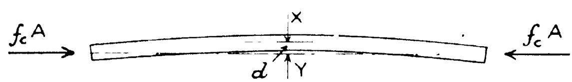


FIG. 24.

the first sign of yielding is a slight flexure to one side. When this state occurs, there is not only a direct compressive stress over any section XY, but there is also a bending moment of amount $f_c \cdot A \cdot d$, the effect of which is to superpose an additional tensile stress upon the convex side Y, and a further compressive stress upon the concave side X. When sideways flexure once commences, it usually continues until the strut finally breaks down with very little additional load.

There are certain formulæ for expressing the crippling loads of struts, which are based upon the assumptions of perfect homogeneity of the material, perfect initial straightness of the strut, and correct centrality of the load; these conditions are only approximated to in practice, for struts are seldom entirely straight or are loaded quite centrally.

In all cases in which the length is greater than one and a half times the least cross-sectional dimension, the member must be treated as a strut, and not as a simple compression block.

* For the results of tests upon short columns see p. 102.

Failure of Thin-Walled Tubes.*

In the case of thin hollow columns, such as metal tubes and hollow spars, if the thickness of the material is less than a certain proportion of the least sectional width, the strut will not fail in the manner indicated above, but by a local buckling or secondary flexure, which occurs at a much lower value of the crippling stress than if failure occurred by sideways flexure In the case of metal tubes, the thickness should not be less than about one-fifth of the diameter, otherwise pronounced crinkling will occur at the maximum load.

Formulæ for Crippling Loads of Struts.

Most of the formulæ employed for expressing the breaking loads of struts are based upon rational or theoretically derived formulæ; but in nearly all cases the constants or coefficients are derived from experiment, and often embody corrections for departures from the hypothetical conditions assumed.

All of the better known formulæ agree in expressing the fact that the value of the crippling load depends upon the ratio, $\dfrac{\text{Length of strut}}{\text{Least moment of inertia of the cross-section}}$, or, as it is called, the *Slenderness Ratio.*†

It is well known that a strut always fails by bending in the direction in which the least moment of inertia occurs. In the design of struts, therefore, it must be remembered that it is the value of this least moment of inertia, other things being equal, which determines the strength of the strut.

In some formulæ, for example the Gordon one, the value of the least width is employed in place of the least moment of inertia, or radius of gyration; the constants being modified accordingly.

Values of the least radii of gyration for typical strut sections are given in Table XI. on p. 61.

* Also see "Design of Aeroplane Struts," W H Barling and H. A Webb, *Aeron. Journ.*, October, 1918

† The least radius of gyration is often employed in place of the moment of inertia in this connexion.

The manner in which the ends of a strut are fixed affects the value of the crippling load to a considerable extent, and therefore in all strut test results the nature of the end fixing should be specified.

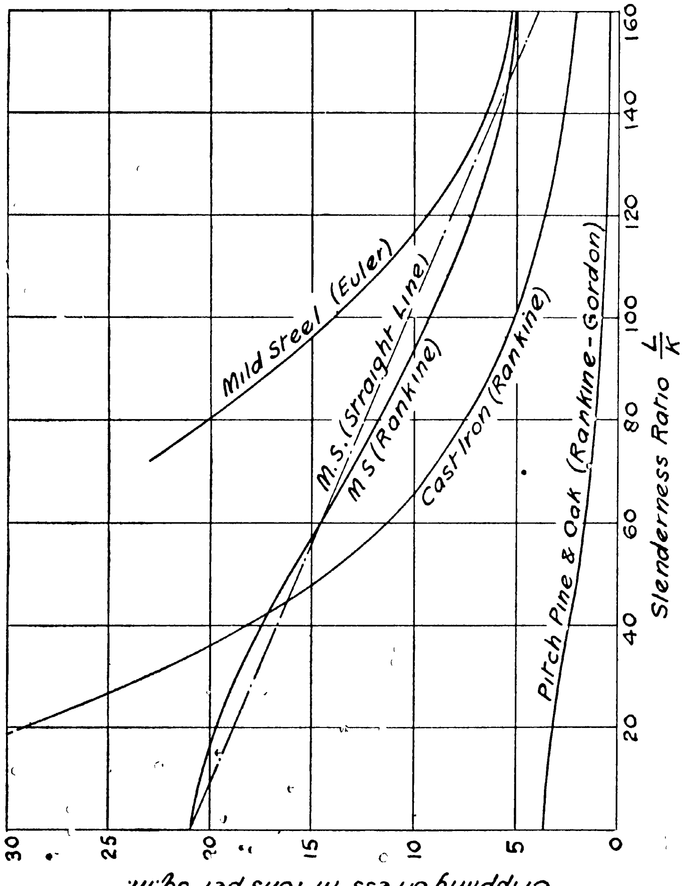


Fig. 24a.—Metal and Wooden Strut Formulæ Results (Rounded or Hinged Ends).

The crippling load of a given strut having rigidly fixed ends is about four times that of the same strut having hard rounded ends. Fig. 24a shows graphically the results given by the

TABLE XI.

Least Radii of Gyration of Strut Sections.

Shape of Cross-Section of Strut.	*Least Radius of Gyration*
Circular section of diameter = D	0·25 d.
Hollow circular section diameters D and d ..	$0{\cdot}25\sqrt{D^2+d^2}$.
Square section of side = b	0·289 b.
Rectangular section long side = d; short side = b	0·289 d.
Thin square cell of side = b	0·408 b
Thin circular cell of diameter = d	0·354 d.
Elliptical section major and minor axes a and b	0·444 b.
Equal angle section (sides = b)	0·204 b.
Equal cruciform section (sides = b)	0·204 b.

different formulæ for the strength of steel and cast-iron struts, with hinged ends.

Euler's Formula.—This is based upon theoretical considerations and is intended to apply to the case of long struts in which the slenderness ratio is not less than about 90. The usual form is as follows:

The crippling load $P = n \cdot \frac{\pi^2 EI}{l^2} = n \cdot \pi^2 EA \div \left(\frac{l}{k}\right)^2$ pounds,

where E = modulus of elasticity in pounds per square inch, I = the least moment of inertia about an axis through the C.G. of the cross-section in inch units, l is the length of strut in inches, k is the corresponding least radius of gyration in inches, and A is the cross-sectional area in square inches ($I = A \cdot k^2$).

The value of the constant n depends upon the mode of fixing of the ends; the following table gives the values of n for the more important end-fixing conditions:

TABLE XII.

Values of Constant n in Euler's Formula.

Mode of End Fixture.	*Value of* n.
1. Both ends rounded, or hinged, so that strut is free to incline in any direction, but the ends cannot move bodily sideways	1
2. Both ends fixed, and forced to remain parallel to the direction of the thrust	4
3 One end fixed rigidly, and the other rounded or hinged but not free to move bodily sideways	2·25
4. One end fixed rigidly, and one rounded or hinged, but free to move bodily sideways	0·25
5. Both ends fixed in direction, but one end free to move bodily sideways	1

TABLE XIII.

VALUES OF ELASTIC MODULI USED IN EULER'S FORMULA.

Material.	*Value of* E. (*Pounds per Square Inch.*)
Wrought iron	28,000,000 to 30,000,000
Mild steel	29,000,000 to 30,000,000
Cast steel and alloy steels	29,000,000 to 31,500,000
Phosphor bronze	14,000,000
Aluminium bronze	15,500,000
Gun-metal	11,000,000
Copper (cast)	11,000,000 to 13,000,000
Copper (rolled)	12,300,000 to 16,800,000
Aluminium (cast)	12,500,000
Aluminium (plate)	13,500,000
Ash*	1,600,000
Spruce* (silver)	1,800,000
Hickory*	1,800,000
English oak*	1,450,000
Elm*	1,600,000
Pitch pine*	1,600,000
Red pine*	1,500,000
Honduras mahogany*	1,250,000

The Rankine-Gordon Formula.

This formula is intended to apply equally well to both long and short struts, and it is so arranged that for very long struts—that is to say, by making the length l = infinity in the formula—it gives values corresponding to the Euler formula, whilst for very short struts—that is, when $l = 0$—it gives the ordinary material crushing stress or load.

The formula is as follows, viz.:

$$\text{Crippling stress } p = \frac{f_c}{1 + c \cdot \frac{l^2}{k^2}} \text{ pounds per square inch,}$$

where f_c = the crushing stress for very short columns of the same material, in pounds per square inch;

l = the length, and k the least radius of gyration, in inches;

and c = a constant depending upon the material and the mode of end-fixing.

The following values for f_c and c represent the average of the more reliable published values.

* Average values, along the grain, for good well-seasoned timber.

TABLE XIV.

VALUES OF CONSTANTS IN RANKINE-GORDON FORMULA.

Material.	*Value of Constant* f_c. *(Pounds Square Inch.)*	*Value of Constant* c. *(For Rounded or Pin-Jointed Struts.)*
Wrought iron	36,000	—
Mild steel	48,000	$\frac{1}{7500}$
Hard or cast steel	60,000 to 70,000	$\frac{1}{5000}$
Cast iron	60,000 to 80,000	$\frac{1}{1600}$
Pitch pine* and oak	8000	$\frac{1}{3000}$
Ash*	6000	$\frac{1}{3000}$
Spruce*	5000	$\frac{1}{3000}$

Note 1.—When using the formula for struts with fixed ends another constant $c_1 = 4c$ must be used.

Note 2.—Curves of crippling strengths for different timbers are given in Vol II † of this book

The Gordon Formula.

This formula closely resembles the preceding one, the only difference being that instead of employing the least radius of gyration k, the least width of the cross-section b is used, thus:

$$p = \frac{f_c}{1 + a\frac{l^2}{b^2}}$$

for rounded ends or pin joints.

The relation between the constants in the two formulæ is as follows—namely:

$$\frac{c}{k^2} = \frac{a}{b^2} \text{ or } a = c \cdot \frac{b^2}{k^2}$$

The following are the values of a for certain commonly occurring cross-sections, the value of f_c being the same as in the preceding case:

* Average values, along the grain, for well-seasoned good grade timbers.
† "Non-Ferrous and Organic Materials"

TABLE XV.

VALUES OF CONSTANT *a* IN GORDON FORMULA.

Form of Section.	*Values of Constant* a.			
	Mild Steel.	*Wrot. Iron.*	*Cast Iron.*	*Timber.*
Solid circle	$\frac{1}{75}$	$\frac{1}{500}$	$\frac{1}{110}$	$\frac{1}{125}$
Solid rectangle	$\frac{1}{500}$	$\frac{1}{700}$	$\frac{1}{125}$	$\frac{1}{150}$
Hollow circle	$\frac{1}{600}$	$\frac{1}{800}$	$\frac{1}{180}$	$\frac{1}{200}$
Hollow rectangle	$\frac{1}{800}$	$\frac{1}{1100}$	$\frac{1}{190}$	$\frac{1}{250}$
L, T, H or cruciform section with sides equal to *b* .	$\frac{1}{300}$	$\frac{1}{400}$	$\frac{1}{90}$	$\frac{1}{100}$
Built-up sections	$\frac{1}{400}$	$\frac{1}{550}$	—	—

Approximate Straight-Line Formulæ.

These formulæ, which depend upon the assumption that between certain limits the curve expressing the relation between f_c and $\frac{l}{k}$ is a straight line, are employed for approximate purposes in America. A typical one is the following—namely:

$$p = f_c\left(1 - e \cdot \frac{l}{k}\right)$$

The values of *e* are as follows:

MATERIAL.

	Wrought Iron.	*Cast Iron.*	*Mild Steel.*	*Timber.*
Value of e ..	0·0053	0·0080	0·0053	0·0083

The values given, for the constant *e*, vary in value according to different authorities, the differences being no doubt due to experimental errors, and the different qualities of materials. Another straight-line formula for hinged silver-spruce struts is given in Vol. II. of this work.

In the case of struts loaded eccentrically, or subjected to

a side or lateral bending moment, the crippling loads become less; for a fuller discussion of these cases and other stress problems the reader is referred to the following works:

"The Strength of Materials," E. S. Andrews. (Chapman and Hall.)

"The Strength of Materials," J. A. Ewing. (Cambridge Univ. Press.)

"The Theory of Structures," A. Morley. (Longmans and Co.)

"Applied Mechanics," Professor Perry. (Cassell and Co.)

"Mechanics Applied to Engineering," Goodman.

And to papers upon struts, in—

Proc. Inst. Mech. Engrs., 1905.

Engineering, July 14, 1905; January 10, 1908; July 2, 1909; January 14, 1910; and March 31, 1911: by Dr. W. E. Lilly; July 26 and August 2, 1912, by H. V. Hutt; August 22, 1912, by R. V. Southwell; September 21, 1917, by A. Morley

Also *vide*—

"Struts of Conical Taper," H. A. Webb and E. D. Lang, *Aero. Journ.*, April, 1919.

"Design of Aeroplane Struts," H. A. Webb and W. H. Barling, *Aero. Journ.*, October, 1919.

CHAPTER II

THE PROPERTIES OF MATERIALS UNDER TEST

The Properties of Materials under Test.—Metals.

THE previous chapter dealt with the stresses to which materials are subjected as viewed from the theoretical side. It is proposed to consider the actual behaviour of materials under different kinds of tests in the present chapter; for this purpose it is deemed advisable to deal with the properties of metals separately in the present chapter, and to consider the properties of timbers and other miscellaneous materials in the respective chapters devoted to these,* in order that each chapter may be more or less complete in itself.

Definitions.

The definition of elastic materials has already been given.†

Malleability is the property which enables a material to be beaten, hammered, or rolled out into thin sheets without fracture or detrimental qualities.

Ductility † is the property whereby a material may be rolled or drawn out by tension into a smaller section. It is this property that is taken advantage of when materials are drawn out into wire.

Materials such as iron, steel, copper, and others, are noted for their ductility; these materials also possess a certain degree of elasticity and plasticity.

Plasticity is the property of a material in which any stress produces a permanent strain; it is the opposite effect to that produced in an elastic material. This property of certain

* "Non-Ferrous and Organic Materials," Vol. II.

† Tables of Malleability and Ductility are given in Appendix II.

metals enables them to "flow" when under the influence of certain stresses. The behaviour of lead under stress is an example of this property.

Commercially, the plastic property is utilized in such processes as "forging," stamping, welding, squirting of lead pipes, making of white-metal bearings, type, etc.

Hardness* is the power of a material to resist indentation by another material. It is usually taken as a measure of the resistance to wear, of metals.

Brittleness denotes the want of *ductility* or *malleability*.

The above properties are not constant for the same material, but vary, relatively, according to the state of the material; for example, the hardness of steel will depend upon the treatment to which it has been subjected. Thus, steel possesses various degrees of hardness according to whether it is annealed, forged or hammered, hardened, or hardened and tempered.

The property of ductility, it should be remembered, is not possessed by elastic materials. It is only after a material has been stressed beyond the elastic limit that it exhibits ductility.

For engineering purposes a material which ultimately shows much ductility, after the elastic limit is passed, is to be preferred, for in the case of many structures the elongating of one member may cause a better distribution of the loads upon the others, and thus relieve the load, to some extent, upon itself.

Behaviour of Metals in Tension.

The simplest test to which a material is subjected in practice is the tensile one. In many cases the tensile test result is the sole criterion of the suitability of the material for a given purpose; moreover, there is often a relation between the tensile properties and the other properties such as the hardness, compressibility, or shearing strength, so that it is often only necessary to make a tensile test in order to deduce approximately the other essential strength properties. Thus in

* For methods of testing hardnesses see p. 144.

the case of most mild steels, the "hardness number" is related to the tensile strength, the tensile and compressive strengths are usually the same, and the shearing strength is a definite fraction (usually about 0·7 to 0·75) of the tensile strength. The quantities usually measured in tensile tests are: (1) The values of the tensile stress at the elastic, yield, and breaking loads; (2) the extension upon a given length; and (3) the reduction of area at fracture.

It is interesting to study the behaviour of a typical metal such as mild steel under a gradually increasing tensile stress. For this purpose, it is necessary to measure or record the corresponding strains, and it is convenient to draw a diagram of corresponding stresses and strains.* A specimen of the correct proportions† is cut from the mass of metal, the properties of which it is desired to know, and the specimen is placed in the *grips* of the *testing machine.*† The strains produced, when the tensile load is applied, are usually measured by some form of *extensometer*‡—that is to say, an instrument for measuring, usually by means of magnification systems, the very small changes produced in length.

In some testing machines an autographic apparatus is provided for actually drawing to scale the stress-strain diagram during a test,§ and the curve exhibits the properties of the material right up to the breaking-point. Fig. 25 illustrates a typical stress-strain curve for mild steel, for both tensile and compressive stresses.

The strains produced by small stresses are extremely small, usually of the order of from about $\frac{1}{15}$ per cent. to $\frac{1}{20}$ per cent. for stresses of about 4 per cent. of the breaking-load value.

As the stress is increased upon the specimen, the strains increase in proportion, very nearly according to Hooke's law, right up to a certain value of the stress (indicated by A in

* Fig. 3 shows a typical diagram for steel, and illustrates the nomenclature employed.

† For shapes and dimensions of test pieces see p. 74 *et seq.*

‡ See p. 186.

§ As shown in Fig. 82.

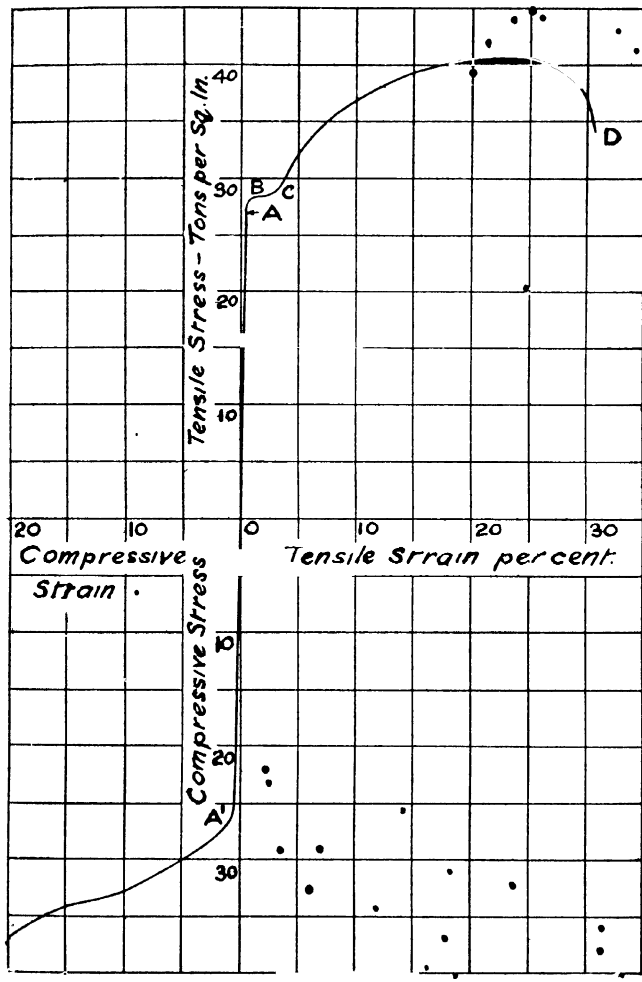


FIG. 25.—STRESS STRAIN DIAGRAM FOR "40-TON" STEEL.

Fig. 25), above which any further stress increase does not cause a proportionate strain increase. The stress value at this point is termed the *Elastic Limit*. The line OA is straight

for iron and most kinds of annealed steels, but is curved for cast iron, and hardened high carbon and alloy steels, copper and similar metals.

British Standard Definitions of Yield Point and Elastic Limit.

Elastic Limit.—The elastic limit is the point at which the extensions cease to be proportional to the loads. In a stress-strain diagram plotted to a large scale it is the point where the diagram ceases to be a straight line and becomes curved.

Note.—The elastic limit can only be determined by the skilful use of very delicate instruments and by the measurement of the extensions for small successive increments of load. It is impossible to determine it in ordinary commercial testing.

Yield Point.—The yield point is the point where the extension of the bar increases without increase of load.

Practical Definition of Yield Point.—The yield point is the load per square inch at which a distinctly visible increase occurs in the distance between gauge points on the test piece, observed by using dividers; or at which when the load is increased at a moderately fast rate there is a distinct drop of the testing machine lever, or, in hydraulic machines, of the gauge finger.

Note.—A steel test piece at the yield point shows rapidly a large increase of extension amounting to more than $\frac{1}{200}$ of the gauge length. The point is strongly marked in a stress-strain diagram.

Beyond the elastic limit, if the stress is gradually increased, the material suddenly draws out, or elongates, by an amount usually greater than the whole amount of the earlier elastic extension. The value of the stress at this point is termed the *Yield Point.* This phenomenon, which is more marked in softer than in hard steels, is indicated on the diagram (Fig. 25) by the portion BC of the curve. In tests upon specimens of 8 inches length, or above, the yield point can be readily determined by making two centre punch marks at a distance, say, of 5 inches apart, and setting a pair of sharp dividers to correspond. If a series of arcs be struck, as the load is

applied, from one point as centre, past the other point, the sudden elongation is easily discernible from the corresponding separation of the arcs.

The subsequent extensions of the specimen can also be readily measured with dividers and a suitable rule or scale.

Beyond the yield point, ductile extensions occur, and the strains become increasingly greater for the same stress increments.

It has been found that the greater part of the strains for a given stress increment, beyond the yield point, occurs almost as soon as the stress is increased, but that there is a much smaller part of the strain which takes a certain amount of time to develop, the stress being kept constant. This phenomenon is known as "creeping."

It will be thus seen that the rate at which the load is applied to the specimen influences the amount of the non-elastic strain; for this reason the *rate of loading* is often specified in tensile tests.

Another significant property, which accompanies the strain beyond the yield point, consists in a gradual reduction of the cross-sectional area, almost in direct proportion to the strain, so that the volume of the test-piece tends to remain constant.

An increased stress beyond the yield point, as previously mentioned, is accompanied by gradually increasing strains, as shown by the portion of the curve CD (Fig. 25), and the flow of metal continues, until, after the maximum value of the stress is reached, the flow increases; this is evident by the gradual formation of a "waist" at about the centre of the parallel portion of the specimen (Fig. 34).

Beyond the maximum stress value,* the specimen goes on extending without further load, and in many cases the load may be reduced, while the specimen draws out until it breaks;

* Here the value is that calculated upon the original cross-section. The difference between this "apparent" and the "real" stress is referred to upon p. 80.

this effect is indicated by the downward inclination of the curve at the breaking point D.

The value of the maximum stress is known as the *Tensile* or *Ultimate Strength*, the *Tenacity* or *Breaking Stress*.

Elongation of Specimen.—Ductility.

The usual indication accepted as evidence of the ductility of a material is the percentage elongation at fracture; for many purposes it is usual to specify the limits of elongation which the material must comply with.

The percentage elongation depends, for the same material, upon the shape and length of the test specimen. For example, if the extensions be measured upon a round bar of, say, 1 inch diameter, and 8 inches length, they will be found to be appreciably greater than those measured upon a ½-inch diameter bar of the same length; this is due to the fact that the greatest part of the elongation of a specimen occurs over a short distance (from 3 to 4 diameters), about the centre of the specimen.

The table on p. 73 gives the actual extensions, in inches, for each 1-inch length of the specimen, along the whole gauge length. The places of fracture are indicated by means of an asterisk, and at these places the local extensions will be seen to be very great, as compared with those of more remote sections.

For this reason, it would be more accurate to always compare results of tests upon geometrically similar specimens;* the English system adopted by the Engineering Standards Committee employs a standard length of 8 inches, without special reference to the cross-sectional area. Comparisons of elongations can only therefore be directly made between the same shapes and sizes of specimens, or of geometrically similar specimens. Otherwise, it is necessary to apply a correction to the elongations, for comparison purposes.

* One method much used on the Continent requires all specimens to be similar, according to the relation $l=11{\cdot}3\sqrt{a}$, where l=length and a=cross-sectional area in the same units.

TABLE XVI.

ELONGATIONS AT DIFFERENT PLACES ALONG TENSION SPECIMEN. (Unwin.)

Material.	*Distance in Inches from One End of Bar.*											
	1	2	3	4	5	6	7	8	9	10	11	12
Rivet iron (10-inch bar)	0·17	0·195	0·23	0·51*	0·26	0·23	0·25	0·23	0·23	0·18	—	—
Axle steel (12-inch bar)	0·16	0·17	0·21	0·21	0·18	0·17	0·21	0·65*	0·46	0·17	0·13	0·10
Brass (10-inch bar)	0·23	0·20	0·20	0·30*	0·21	0·22	0·24	0·21	0·21	0·21	—	—
Lead (9-inch bar)	0·18	0·15	0·30	0·17	0·14	0·22	0·16	0·17	1·01*	—	—	—

In the case of a test piece of mild steel, 8 inches in parallel length, the extension, at fracture, for the central 1-inch portion was 0·50 inch, or 50 per cent., whereas on the end 1-inch portions it was 0·23 inch, or 23 per cent.; the mean extension was 34 per cent., reckoned upon the 8-inch length.

Within the elastic limit for materials such as mild steel, iron, and rolled metals, the elongation x over a given length l is proportional to the stress p, as shown upon page 10.

The extension per unit length $\lambda = \frac{x}{l} = E \cdot p$, where E is the elastic modulus.

If E and p are both in pounds or tons per square inch, x and l must be in the same units (usually in inches).

Many materials, such as cast iron, copper, hardened alloy-steels, and cements, are not perfectly elastic, and therefore do not obey Hooke's law; the extensions, in most cases, even for small stresses, are not proportional to the stresses. In such cases the extension per unit length λ is given by—

$$\lambda = c \cdot p^n,$$

* Specimen broke at this place.

where c is a constant, having a value of the same order as E, and n is a constant, which is greater than 1 for cast iron, copper, zinc, and cement, and less than 1 for leather, fabric, etc.

Unwin* has shown, as a result of a large number of tests, that percentage elongation $e = 100\lambda$ can be expressed in terms of the gauge length l inches, by means of the formula—

$$e = 100\lambda = \frac{c\sqrt{A}}{l} + b,$$

where c and b are constants for different materials, and A is the original cross-sectional area in square inches.

The following values of the constants c and b are given by Unwin:

TABLE XVII.

VALUES OF CONSTANTS IN UNWIN'S ELONGATION FORMULA.

Material.	c.	b.
Mild steel†	70·0	18·0
Tyre steel†	27·2	13·1
Axle steel†	39·2	20·6
Gun-metal (cast)	8·3	10·6
Brass (rolled)	101·6	9·7
Copper (rolled)	84·0	0·8
Copper (rolled—annealed)	125·0	35·0

Forms of British Standard Tensile Test Pieces.

Test Piece A (Fig. 26).—The widths of the test pieces for plates were selected to comply with the two following conditions: (1) As the great bulk of plates to be tested are from $\frac{3}{8}$ inch to $\frac{7}{8}$ inch thick, it was desirable for the sake of convenience that the test pieces for such plates should be of uniform width, and, in accordance with very general practice, a width of 2 inches was selected. (2) With a test piece of a given form, the percentage of elongation was found to be less for thick plates

* "The Testing of Materials," p 100, by W. C. Unwin.

† Mean values.

than for thin ones; with steel of the same quality in other respects it was desirable therefore to choose widths of test piece which would be slightly in favour of the thicker plates. This is secured with the widths selected for the standard test piece of form A.

Test Piece B (Fig. 27).—All test pieces of forms B are strictly similar, and for the same material give the same percentage

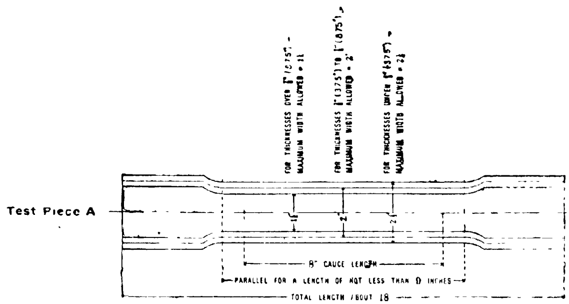


FIG. 26.

of elongation. They are nearly similar to a test piece of form A, 8 inches in gauge length, 2 inches wide, and ⅜ inch thick.

Test Pieces C, D, E (Figs. 28, 29 and 30).—These were arranged to meet the very common practice of making test pieces for forgings, axles, tyres, etc , of either ¼ square inch or ½ square

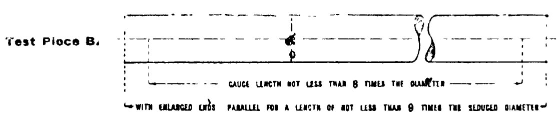


FIG. 27.

inch in sectional area. With the gauge lengths decided upon these three forms are very nearly similar, and, for a given material, give very approximately the same percentage of elongation. Though not exactly, they are approximately similar to the standard test piece F, and for the same material give a nearly identical, but slightly greater, percentage of elongation.

Test Piece F (for test pieces over 1 inch diameter) (Fig. 31).—In some testing machines it was found inconvenient to use form B for bars of over 1 inch in diameter, and form F of half the gauge length is designed to meet such cases. For a given material the percentage of elongation with test piece F is greater than with test piece B, and this difference is provided for in the British Standard Specifications.

FIG. 28.

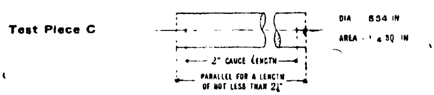


FIG. 29.

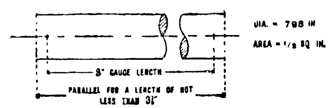


FIG. 30.

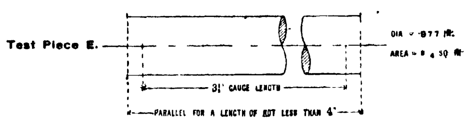
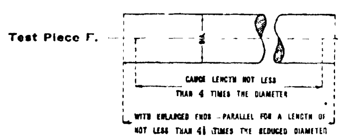


FIG. 31.



Form of Ends.—In the case of the round test pieces B, C, D, E, and F, the form of the ends is to be as required in order to suit the various methods employed for gripping the test piece. When enlarged ends are used, the length of the parallel portion of the test piece must in no case be less than that noted on the diagrams.

Forms of International Aircraft Standard Tensile Test Pieces. —Specifications.

Physical Properties and Tests.—(*a*) Physical tests shall be carried out on testing machines of standard make, which are to be kept in good working condition. The manufacturer must satisfy the inspector that the testing machines are at all times properly calibrated.

Tensile Test.—(*b*) To determine whether a specimen has a yield point equal to or greater than that specified the procedure shall be as follows: A line shall be described on the test piece with a punch mark as centre, and with a radius of about 2 inches (50·8 millimetres) when possible; the specified load shall then be applied, removed, and a second line scribed with the same radius and the same centre; if two lines are then seen on the test piece, indicating that permanent elongation has occurred, it shall be considered that the specimen has not passed the yield-point test. If the manufacturer desires, the yield point may be determined by an approved autographic or extensometer method.

(*c*) The elastic or the proportional limit, when called for, shall be determined with an extensometer reading to at least 0·002 inch (0·05 millimetre). It shall be attached to the specimen at the gauge marks and not to the shoulders of the specimen nor to any part of the testing machine. The elastic limit is defined as the greatest load per unit of original cross-section which does not produce a permanent set. The proportional limit is the load per unit of original cross-section at which the deformation ceases to be proportional to the load.

Test Specimens.—(*i*) Tension, bend, and impact test specimens shall be taken from the rolled or forged material, except that in the case of irregularly shaped forgings they may be taken from a full-sized prolongation. Specimens shall not be annealed or otherwise treated, except as provided in the individual specifications.

(*j*) Tension, bend, and impact test specimens for rolled material which is to be annealed or otherwise treated before use shall be cut from properly annealed or similarly treated short lengths of the full section of the piece, and for forged material from the treated forgings.

(*k*) The axis of tension, bend, and impact test specimens for rolled bars and forgings of uniform cross-section over $1\frac{1}{2}$ inches (38·10 millimetres) in thickness or diameter and for forgings of irregular section, when practicable, shall be located at a point midway between the centre and surface when solid

and at any point between the inner and outer surfaces of the wall when bored, and shall be parallel to the axis of the piece in the direction in which the metal is drawn.

(*l*) Tension test for specimens for bars shall conform to the dimensions shown in Fig. 32. The ends shall be of a form to fit the holders of the testing machine in such a way that the

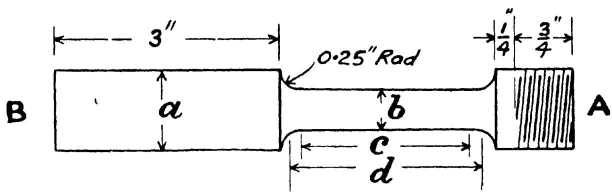


FIG. 32.

load shall be axial; test specimens representing heat-treated or brittle materials shall have threaded ends or ends so made as to permit of testing material, using a ball-and-socket chuck.

(*m*) Tension and bend test specimens for plates, sheets, and shapes shall be of the full thickness of material as rolled.

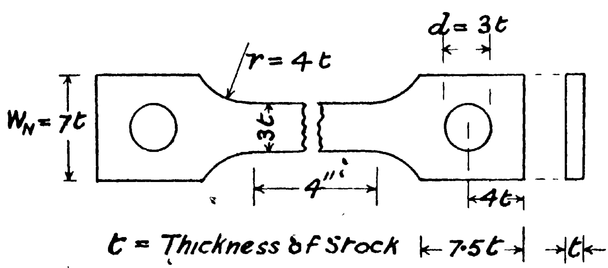


FIG. 33.

Tensile-test specimens for sheets or plates shall be machined to the form and dimensions shown in Fig. 33. Bend-test specimens for sheets shall have a width of 1·5 inches (38·10 millimetres) and a minimum length of 8 inches (203·2 millimetres). Test specimens shall not be hammered in order to straighten them, nor may they be tempered, annealed, or

otherwise treated unless specifically noted. Impact-test specimens are to be rectangular in section and shall be notched on one side. They are to have the form shown in the sketch, Fig. 60.

Selection of Test Specimens.—A sufficient number of test specimens will be selected by the inspector from each lot of material submitted to satisfy him of the quality of the material. If any test specimen shows defective machining or develops flaws, it may be discarded; in which case the manufacturer and the purchaser or his representative shall agree upon the selection of another specimen in its stead.

Marking and Identification.—(*a*) It shall be the duty of the manufacturer to provide that manufacturing identification marks, such as heat numbers, shall be readily available at the time of inspection of the finished material to the inspector, and further that materials shall be grouped when possible by heat or melt numbers.

Test specimens in accordance with the sketch Fig. 33, shall apply to sheet $\frac{1}{5}$ inch (5·08 millimetres) (No. 6 U.S. standard gauge) and up in thickness. Below $\frac{1}{5}$ inch (5·08 millimetres) in thickness w and d shall be $\frac{1}{2}$ inch (12·70 millimetres), h $\frac{1}{2}$ inch (12·70 millimetres), and wn 1 inch (25·40 millimetres). The percentage of elongation may be determined on either 2 or 4 inches (50·80 millimetres or 101·60 millimetres).

Soft materials of light gauge are apt to fail in detail under the pin. Specimens representing these materials may be gripped in the jaws of the testing machine. Drilling is omitted.

The specimens may be reduced in width by not more than 0·003 inch (0·08 millimetre) over the centre half of the gauge length in order that fracture may occur there.

Reduction of Area.

The shapes of a test piece after a tensile test, to fracture, for the case of mild steel, is shown in Fig. 34; the formation of a "waist" is marked in the case of ductile materials, such as iron, mild steel, and copper. The percentage area contraction is the same as the percentage elongation,

within the limits of elasticity, when the latter is estimated upon the *final* length; this must be the case if the volume of the gauged portion is constant throughout. The tensile strength of a material is, for most practical purposes, reckoned upon the original cross-sectional area and the autographic curves of stress-strain show that near the breaking-point this "apparent stress" nearly always decreases.

The "true stress"—that is to say, the stress as reckoned upon the actual area of the smallest section—actually increases, however, since the area decreases, and the value of this real stress may be anything up to 30 or 40 per cent

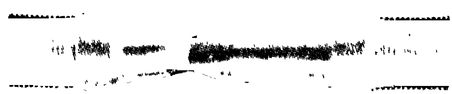


FIG. 34.—SHAPE OF MILD STEEL TENSILE TEST SPECIMEN AT FRACTURE.

higher. Thus in the case of the mild steel specimen mentioned in the preceding paragraph, the area at fracture was 55 per cent. of the original. The true stress at fracture was therefore $\frac{100}{0\cdot55}$ or 1·82 of the apparent stress.

The curves shown in Fig. 35 illustrate the difference between the real and apparent stresses, for both tension and compression in the case of a ductile material like steel. The material at the fractured ends usually presents the appearance of a conical portion, roughly of 45° slope on the one side, and a corresponding conical recess upon the other side.

Materials such as wrought iron and mild steel, which possess both plasticity and relatively high tensile strength, show the greatest area reduction, whereas hard or brittle materials like cast iron or hard steel show only a small area reduction.

In general, the higher the tensile strength, the smaller the area reduction; there are, of course, exceptions to this rule, but it will be found to hold good in most cases. The same

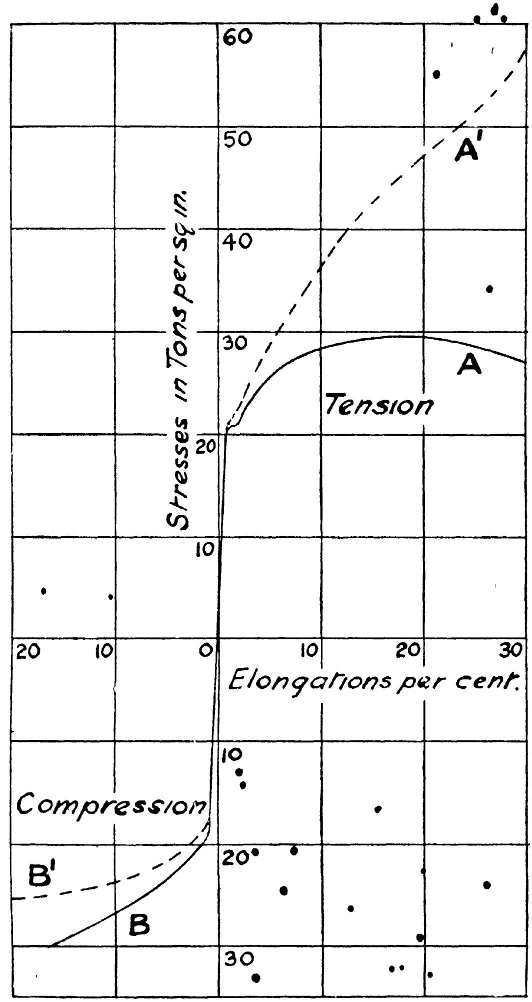


FIG. 35.—REAL AND APPARENT STRESS CURVES.

remarks apply in the case of the elongation as shown in the following table:

I.

TABLE XVIII.

PROPERTIES OF DIFFERENT FERROUS METALS.

Material.	Tons per Square Inch			Percentage Elongation.	Percentage Reduction of Area.
	Elastic Limit.	Yield Point	Tensile Strength		
Wrought iron ..	14·00	17	25·0	30·0	55·0
Mild steel, 0·2 C. ..	14·00	16	30·0	28·0	48·0
Mild steel, 0·35 C	16·00	18	35·0	25·0	45·0
Case-hardening mild steel (annealed)	28·50	—	34·1	44·0	62·2
Case-hardening mild steel (hardened)	34·80		46·4	3·2*	8·1
Nickel steel 3 per cent Ni (annealed)	29·07	—	44·3	31·5	53·8
Nickel steel 3 per cent Ni (oil tempered)	80·18	-	83·5	16·0	43·4
Nickel-chrome steel (annealed)	43·50	-	55·0	22·0	64·0
Nickel-chrome steel (air hardened)	86·00		113·0	13·0	33·0
Nickel case-hardening steel (normalized)	26·00		33·0	35·0	65·0
Nickel case-hardening steel (case-hardened)	60·00	—	69·0	18·0	61·0
Chrome-vanadium steel (as rolled)	46·40	--	57·1	25·0	61·2
Chrome-vanadium steel (heat treated)	106·20	—	120·4	8·0	19·9
Spring steel (tempered) ..	85–95		95–305	8–12	25–30
Steel castings (automobile)	20·50	—	0·30	22–25	35–40

Behaviour of Metals in Tension and Compression.

The tensile properties of iron, carbon, and alloy steels are shown in Fig. 36, the curves representing typical test results for the materials shown. It will be observed that the elastic portions of the curves are nearly the same for all of the metals, although the scale is too small to show any small differences; the elastic moduli for these materials are therefore approximately the same.

In the case of cast iron, high carbon and alloy steels† the

* On 5-inch length.

† The effects are most enhanced in the hardened and tempered steels, more especially in the high-tensile steels as shown in Table XVIII.

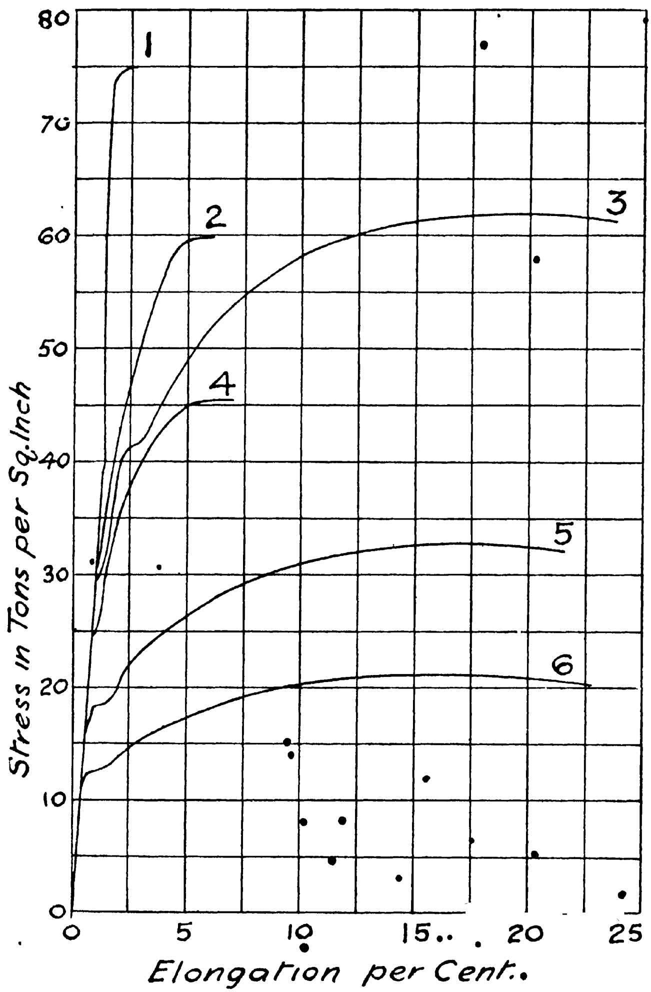


FIG. 36.—TENSILE STRESS-STRAIN CURVES.

1, Nickel-chrome steel, air-hardened; 2, tool steel, unannealed; 3, nickel chrome steel, unannealed; 4, crucible steel, untreated; 5, mild steel; 6, wrought iron.

TABLE XIX.

PROPERTIES OF NON-FERROUS ALLOYS AND METALS.*

Material.	*Tons per Square Inch.*			*Elongation per Cent. on 2 Inches*	*Reduction in Area. per Cent.*
	Elastic Limit.	*Yield Point.*	*Tensile Strength.*		
Aluminium (cast) ..	—	—	5–5½	2–3	
Aluminium (rolled, along grain)	4½	—	6½–7½	25·0	—
Aluminium (rolled, across grain)	6	—	6¾–8	10–13	—
Aluminium bronze (10 per cent.)	—	—	38½	26·3	28·0
Copper (cast)	—	—	7–9	10–15	—
Copper (rolled)	—	—	17½	10·0	49·0
Copper (drawn wire) ..	—	—	24–28	0·8–2·0†	—
Delta metal No. 1 (cast)	—	—	41·3	20·0	20·4
Delta metal No. 1 (extruded)	—	—	49·8	26·0	24·9
Delta metal No. 4 (cast)	—	—	23·9	21·0	20·1
Delta metal No. 4 (extruded)	—	—	37·1	27·0	20·0
Duralumin sheet (normal)	16·5	—	27·5	15·0	—
Duralumin sheet (hard) ..	20·0	—	31·0	11·0	—
Duralumin rod (normal ..	16·5	—	26·0	18·0	—
Duralumin rod (hard) ..	21·0	—	32·0	8·0	—
Duralumin wire (normal)	16·5	—	26·0	19·0	—
Duralumin wire (hard) ..	22·5	—	35·0	8·0	—
Gun-metal (cast) (copper, 87; tin, 10; zinc, 3)	7–8	—	13·15	10·0	20·0
Gun-metal bars	—	14-15	28–30	10·0	20·0
Naval brass (aero) ..	—	12–13·5	24–27	30·0	—
Phosphor bronze (rolled) (copper, 93; tin, 6·5; zinc, 0·5)	—	26–30	30–35	5·0	—
Manganese bronze (cast) (copper, 58; zinc, 38; aluminium, etc., 4)	—	13–14	30–35	15·0	—
Muntz metal	—	—	23–26	35·0	59·6
Yellow brass	—	—	24	41·0	61·0
Cast brass	—	—	10–13	24·0	16·4

yield and elastic points are usually very indefinite, and the curve at these values is very smooth as compared with that of mild steel, so that it is difficult to detect the points of elastic and yield stresses.

* For much fuller particulars see Vol. II, "Non Ferrous and Organic Materials."

† On 8-inch lengths.

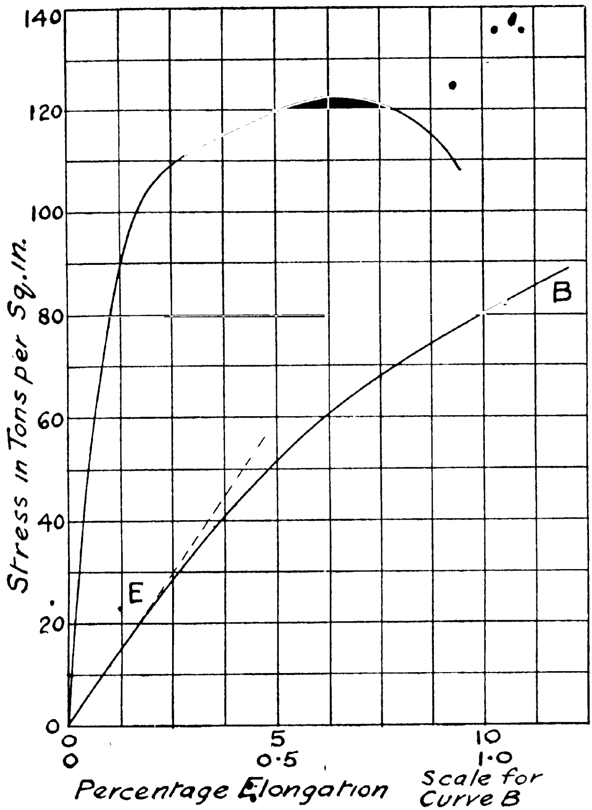


FIG. 37.—STRESS-STRAIN CURVE FOR HARDENED NICKEL-CHROME STEEL (AIR-HARDENED AT 800° C). *E*, Elastic limit. Curve *B* shows the strains magnified ten times.

For very hard steels, such as air-hardened nickel-chrome (of tensile strength 100 to 120 tons per square inch), there is no true elastic limit, or a very low value, usually below 25 tons per square inch.

Typical curves for a nickel-chrome steel, which has been air-hardened after heating to 800° C., is shown in Fig. 37. The composition of this steel is given in the table on p. 86.

TABLE XX.

COMPOSITION OF NICKEL-CHROME STEEL—AIR HARDENING (PERCENTAGES.)

Carbon.	*Silicon.*	*Sulphur.*	*Phosphorus.*	*Manganese.*	*Nickel.*	*Chromium.*	*Iron.*
0·33	0·34	0·041	0·032	0·47	3·54	1·84	93 407

Ductile Materials in Compression.

Compression tests are usually made upon specimens in which the length is about the same as the minimum width, otherwise failure by buckling occurs.

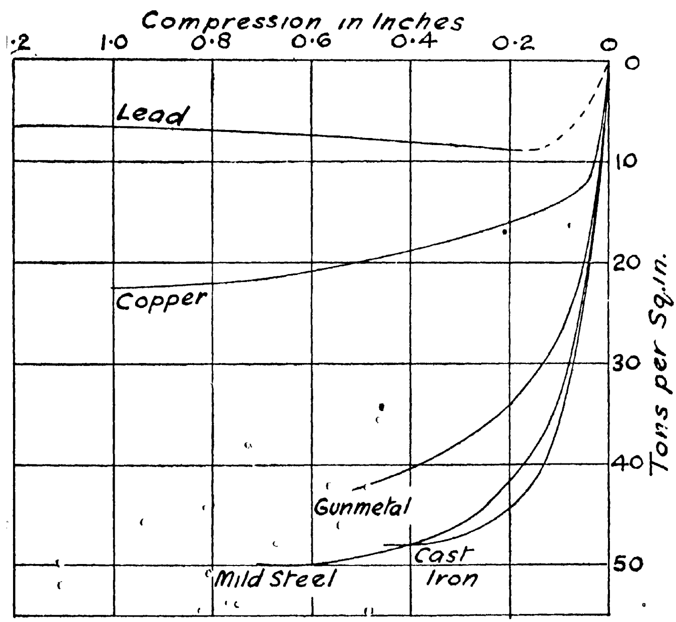


FIG. 37A.—COMPRESSION STRESS-STRAIN CURVES FOR DIFFERENT METALS.

Ductile materials tested in this manner tend to flow outwards under compressive load, and as the load increases the

area of specimen also increases due to this lateral flow, and a state of affairs is soon approximated to in which the ratio $\frac{\text{load}}{\text{area}}$—that is, the compressive strain—becomes nearly constant. The more ductile, or plastic, the material the more nearly constant does the stress become.

Thus for a plastic material, like lead, the stress is practically constant, in compression. Experiments made by Hick upon lead cylinders $2\frac{1}{2}$ inches long by 2 inches diameter, with loads varying up to $5\frac{1}{2}$ tons, showed a progressive reduction in length down to 1·128 inches, and increase in diameter at the centre of 3·16 inches The stress after the first ton or so remained approximately constant at 0·72 ton per square inch.

Unwin has shown that the compressive stresses in plastic materials can be approximately represented by the formula—

$$p = P(1 - \lambda)/w,$$

where p/λ the modulus of elasticity, P the total load, and w the cross-sectional area. p is known as the plastic stress λ is the compression per unit length.

Fig. 37A shows the stress-strain curves for lead, copper, mild steel, cast-iron, and gun-metal

Cast Iron.

Cast iron is another material which has no real yield point, or elastic limit, as the continuously curved stress-strain diagram shown in Fig 38 indicates.

Cast iron, being a brittle material, breaks with little extension, and at a low tensile strength, usually from 8 to 12 tons per square inch.

Owing to its very low elastic limit, or to its absence of a true elastic limit, cast iron takes a definite set for very small stress values, as indicated by the dotted lines in Fig. 38.

The relation between the stress and strain in both tension and compression for cast iron is given by Hodgkinson as follows—namely:

For tension $f_t = 6220e = 1{,}298{,}000e^2$.
For compression $f_c = 5773c = 233{,}500c^2$,

where f_t and f_c are in tons per square inch, and e and c are the relative extensions and compressions per unit length.

Unwin gives the following more exact relations between the same quantities:

$$e = 1{\cdot}503f_t^3 \times 10^{-6} + 1{\cdot}685f_t \times 13^{-4},$$

$$c = 9{\cdot}66\ f_c^3 \times 10^{-8} + 1{\cdot}782f_c \times 10^{-4}.$$

It has been found that the strength of cast-iron bars varies with their size, the smaller diameter bars being the stronger; the difference between bars varying from 1 to 3 square inches is about 25 per cent.

Fig. 38 shows the stress-strain curve for both tension and compression for this material; the dotted line shows the permanent set when the load is removed. Only a portion of the compression curve is shown, as the ultimate strength of cast iron in compression is from 40 to 60 tons per square inch—that is to say, from 4 to 6 times the tensile strength.

In the initial stages of stress the value of Young's modulus (E) is from 6400 to 7500 tons per square inch, according to Unwin.* If the average value of E be taken for, say, the whole range of tensile stretch, it will be much smaller, probably about 4000 tons per square inch, owing to the smaller slope of the stress-strain slope at the higher stress values.

The shear strength of cast iron varies from 6 to 13 tons per square inch, depending upon its grade or quality; the white irons have the higher values.

Fig. 39 shows some typical stress-strain curves for a few non-ferrous metals. These are included for comparison purposes.

In most cases there is no very definite elastic portion of the curve, although there is usually a fairly well-defined yield point.

The above curves should be taken as being typical ones†

* "The Testing of Materials of Construction," Unwin.

† Fuller particulars of the strength properties of non-ferrous metals and alloys are given in Vol. II.

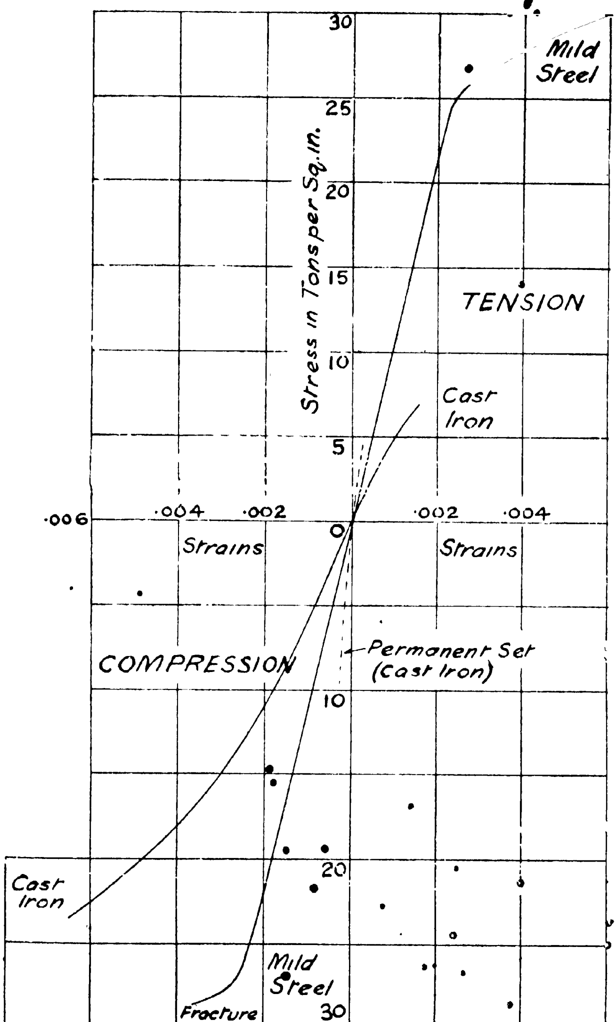


FIG. 38.—ILLUSTRATING BEHAVIOUR OF CAST IRON IN TENSION AND COMPRESSION.

only, for the properties of these metals vary considerably with their composition, treatment, and method of manufacture. The rather indefinite and low elastic limits in the

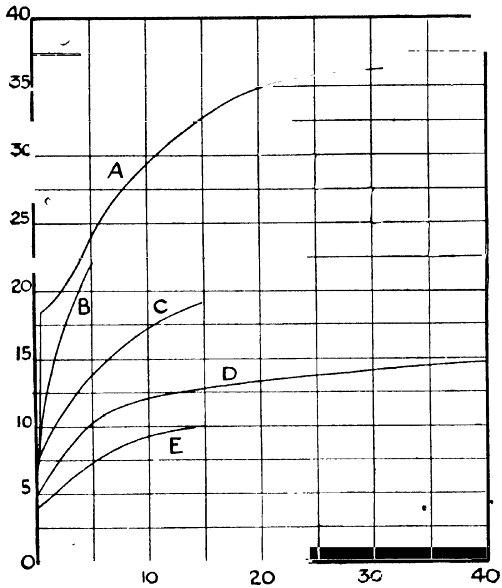


FIG. 39.

A, Aluminium bronze; *B*, hard brass; *C*, annealed brass, *D*, rolled annealed copper; *E*, rolled aluminium.

case of aluminium and copper are related to the plastic properties of these metals, for they flow almost continuously from the commencement of the tensile test.

Utilization of Tensile-Test Results.—The Quality Factor.

The tensile-test results readily obtained include the ultimate stress, the elongation, and reduction of area. Various methods have been suggested for combining these factors, in such a manner that the result, or "quality factor," expresses both the strength and the ductility of the material, or the ductility alone.

Tetmajer proposed the formula—

Quality factor = tensile strength × percentage elongation . . . . (A)

whereas Wöhler suggested the formula—

Tensile strength + percentage contraction of area . . (B)

The formula which is often used in England is—

Quality factor = tensile strength + percentage elongation on given length . . . . (C)

For a good quality of steel forging its value is from 55 to 60, and for high-grade mild steel 50 to 57; for locomotive axle steel it varies from 68 to 76. The quality factor is often specified in connexion with material contracts.

For example, the ductility of gun-metal bars, for aircraft purposes, is sometimes specified by a quality factor = percentage elongation on 2 inches + percentage reduction of area, which must exceed 26 per cent: for medium duralumin bar this factor must exceed 30 per cent. It should be noted, in connexion with this type of specification, that the quality factor often depends upon the size of the plate or bar from which the specimen is taken. Thus for mild steel (0·3 carbon) plates of $\frac{1}{4}$, $\frac{1}{2}$, and $\frac{3}{4}$ inch thickness, respectively, the quality factors (C) are 61, 57, and 55 respectively.

Time Influence in Tensile Tests.

If the tensile load be applied slowly to a steel or iron specimen, the final elongation for the same stress value will be much greater than if the load is applied quickly; this effect is due to the greater flow of metal which the longer period of the former test permits. The ultimate stress is, however, about the same in each case.

If, however, the load be applied in a series of steps, with long time intervals between, there will be a new and higher yield point, a higher breaking load, and a smaller extension.

In a test of this kind upon two similar mild steel specimens, one of which was successively loaded at the rate of $\frac{1}{50}$ of the ultimate load at intervals of 3 minutes, whilst the other was

loaded by the same amounts once every 1200 minutes, the former broke at 90 per cent. of the stress value of the latter, but its extension was 25 per cent., whereas that of the latter was only 8 per cent.

Again, if a steel or iron specimen be stressed to just beyond the elastic limit, and the load be then removed, there will, of course, be a permanent elongation when the load is taken

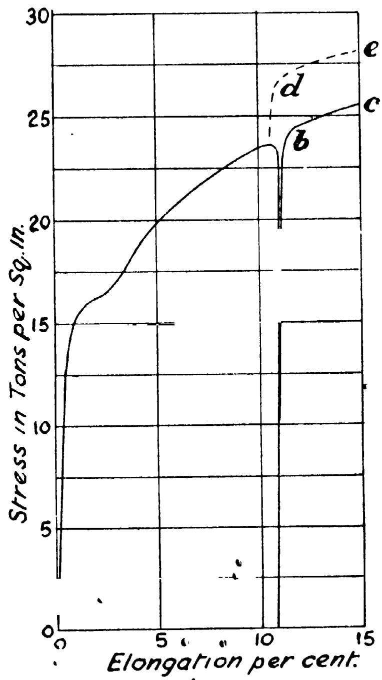


FIG. 40.

right off; but if now the load be applied again, without any appreciable time interval, it will be found that there is a new yield point at about the stress value reached by the previous load just before it was taken off, as shown by the curve* *bc* in Fig. 40. If, however, there is an appreciable

* *Vide* "The Strength of Materials," p. 34, J. A. Ewing.

time interval, say of several hours, between the two loadings, a still higher yield point *d* will be reached.

The effect of repeated stressing beyond the original steady loading elastic limit is also to raise the ultimate strength and to reduce the final elongation; these effects appear to be connected with a process of hardening of the metal.

The material, after such overstraining, loses much of its original elasticity, and even small stresses appear to cause permanent set after the load is removed, although it is true that there is a partial return to its elastic condition after an interval of a day or two. There is no true elastic limit immediately after overstraining, but if a long period of rest is allowed, the elastic limit becomes more definite and at a higher value.

Hysteresis.

Overstrained steel or iron also exhibits the property of hysteresis, when the load is applied gradually to a certain value and taken off at about the same rate. This effect is due to the imperfect elasticity, and the longer the period of time allowed, the less the hysteresis.

The stress-strain curves for an overstrained material take the form of a closed loop, as shown in Fig. 41.

The area of the loop represents the work done on the material, in altering its internal condition; it might be termed the energy wasted internally, in virtue of its imperfect elasticity.

The effect of very slow loading, and unloading, is indicated by the dotted lines in Fig. 41.

Effect of Temperature on Recovery of Elasticity.*

When an overstrained piece of steel or iron is heated for a few minutes in boiling water, it will be found to have recovered its elasticity completely, whilst it will have a higher yield point than the overstrained load value. A bar of mild

* *Vide* paper by J. Muir in Phil. Trans. Roy. Soc., 1899.

steel which is stressed to just beyond the yield point, and then heated to 100° C. for a few minutes, then stressed again to the new yield point, and reheated to 100° C., and so on, will break at a higher load value than in the ordinary way,

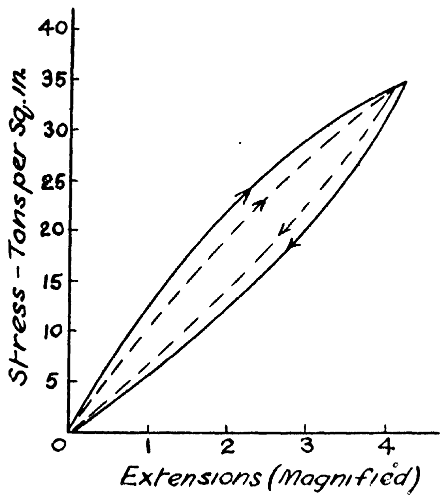


FIG. 41.

and the fracture will be found to resemble that of a hard steel, such as cast steel. Moreover, the extension and area contraction are very much smaller than in the ordinary test.

Annealing.*

When an overstrained piece of steel or iron is heated to redness—that is to say, to from 850° to 950° C.—and is allowed to cool fairly slowly, by immersing it in a bed of ashes, sand, or other non-conducting material, it will be found to have recovered its original state of elasticity, its original yield point, and tensile strength.

This process (which is more fully dealt with in a later chapter) is employed commercially for removing manufacturing and local hardening strains, such as those remaining

* See also p 491 *et seq.*

in bent sheet metal work and cold stamping, in removing local punching and shearing hardnesses, and in softening hard drawn wire, etc.

Local Hardening Effect of Shearing and Punching.

When a bar or piece of steel plate is punched or sheared, the metal around the punched hole or about the sheared edge is badly deformed, and in consequence is considerably harder than that of the rest of the bar or plate.

This local hardening has a marked detrimental effect upon the tensile strength and elongation, for if a flat strip of steel having a punched hole be tested in tension, it will be found to break at a lower stress value than that for a plain drilled plate of the same material. Although experiments upon punched plates are not altogether concordant, yet they generally agree in showing a loss of tensile strength of from 5 to 20 per cent. in iron, and of from 8 to 35 per cent. in steel plates. The greater the thickness of the plate, the less the tensile strength loss from this cause.

The reason for the above effect is that the hardened metal around the hole receives a greater stress intensity, owing to the fact that it is unable to stretch so much as the rest.

The effect of a sheared edge in the case of a metal plate is similar in causing premature fracture at a lower breaking load.

The effects of local hardening around punched holes may be obviated by annealing, or by reamering the hole, after punching; in the case of a sheared edge the hard metal may be removed by planing, or softened by annealing.

The commercial method of making square or other shaped holes by cold drifting round holes results in a similar local hardening around the holes.

Effect of Drilled Holes in Plates.

The tensile strength* of a steel or iron plate having a single hole, or a row of holes perpendicular to the line of

* The term "tensile strength" in all cases denotes the ultimate tensile stress.

pull, has been found to be from 8 to 12 per cent. greater than that of the undrilled plate material; the fracture occurs across the holes. It is believed that the prevention, by reason of the form of the metal near the holes, of local contraction causes a higher tensile strength.*

Effect of Shape of Test Piece.

For exactly the same reason as in the preceding case, the tensile strength of specimens shaped as shown in Fig. 42 will be greater than that of parallel specimens. It may be here mentioned that in ductile materials such as wrought iron or

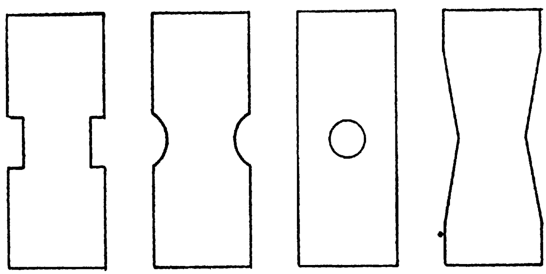


FIG. 42.

mild steel the length of the part which is affected by local contraction is from 6 to 8 times the greatest transverse width, so that for accurate tests the specimen should have a parallel length of at least 8 times its greatest transverse dimension.

The effect of a flaw, nick, or crack, in a specimen is to cause a local stress distribution which is not uniform around the defective part; such a specimen will yield more by tearing, and the fractured surfaces will present a crystalline appearance, as distinct from the usual fibrous form of fracture of ductile materials. The same remarks apply for other types of stress, such as those caused by impact, repetition of loads, and bending.

* Also see Figs. 123 and 125, pp. 243 and 247.

Effect of Temperature upon the Strength of Metals.

Parts of machines such as boilers, internal combustion engine cylinders, valves, etc., are exposed to considerably higher temperatures than atmospheric, and this fact should be taken into account in design work. At ordinary atmospheric temperatures there is no appreciable change in the tensile strength of mild steel or wrought iron. The tensile strength increases continuously from 0° C. to − 200° C., being about 80 per cent. greater at the latter temperature. It also increases from 0° C. to about 200° C. by about 30 per cent., and then falls off continuously from 200° C. up to the melting-point. The loss in tensile strength between 200° C. and 500° C. is from 40 to 50 per cent. of the normal atmospheric value.

The elastic limit falls continuously from atmospheric temperature right up to the highest temperatures at which there is any tensile strength; from 0° C. to 500° C. the elastic limit falls by from 45 to 55 per cent.

The elongation diminishes from 0° C. to about 180° C., and then increases continuously for higher temperatures.

Iron or steel containing an appreciable amount of *phosphorus* becomes brittle at low temperatures; this effect is known as "cold-shortness." The opposite effect—namely, a loss of strength at high temperatures—is known as "red-shortness," and may be due to the presence of too much *sulphur*.

At a "blue heat" it is inadvisable to work steel or iron, as the material becomes brittle when cold. Prolonged exposure of wrought iron to temperatures as low as 60° C. will cause a slight falling off in its strength, and a variation in its magnetic qualities.

Very low temperatures, such as those of liquid gases, have the effect of making the metal brittle, and of diminishing the elongation; the tensile strength increases with progressive decrease of temperature in the case of mild steel and iron. Fig. 43 illustrates the manner in which the tensile strength of iron varies with the temperature.

High-carbon and most alloy steels* are affected by temperature increase, when these steels have been heat-treated in any way. It is well known that the degree of tempering of cast steel, for example, is solely governed by the temperature; any increase of temperature in the case of hardened cast steel above about 100° C. results in a diminution of tensile strength, but in an increased elongation.

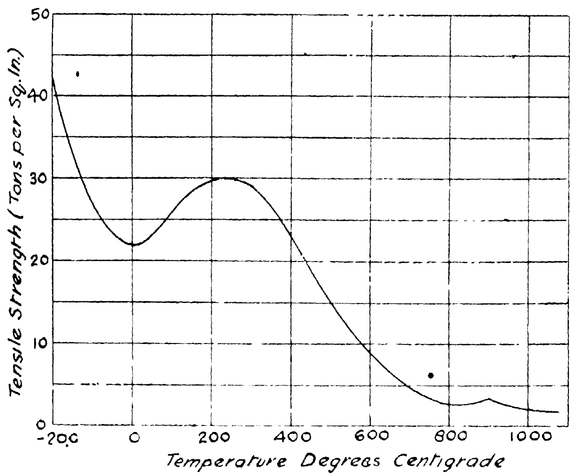


FIG. 43.—EFFECT OF TEMPERATURE UPON TENSILE STRENGTH OF WROUGHT IRON.

Copper and its alloys are greatly affected by temperature changes, and the detrimental effect of high temperatures should be taken into account when this metal or its alloys is employed in steam and internal combustion engine work.

Table XXI.† shows the strengths of several metals of this class at different temperatures.

Unwin gives the following approximate formula for the given metals:
$$f = a - b(t - 60)^2,$$
where f is the tensile strength at any temperature $t°$ F.

* See Figs. 168, 169, and 170.

† "The Testing of Materials of Construction," W. C. Unwin. Longmans, Green and Co.

The values of the constants a and b are given in Table XXII.

The effect of temperature increase upon the properties of cast iron* is to slightly increase its tensile and compressive strength from 0° F. to 900° F., after which these strengths diminish fairly quickly. At 1500° F. the strengths are only about 20 per cent. of the normal values.†

TABLE XXI.

STRENGTH OF COPPER AND ITS ALLOYS AT DIFFERENT TEMPERATURES.

Metal.	Tensile Strength (Tons per Square Inch).				
	60° F.	200° F.	300° F.	400° F.	600° F.
Copper	14·8	14·5	14·0	13·2	10·6
Rolled brass	24·1	23·5	22·5	20·9	15·7
Rolled Delta metal .	31·3	30·5	28·9	26·6	19·4
Cast gun-metal ..	12·1	11·7	10·9	9·7	6·0
Cast brass	12·5	12·0	11·1	9·7	5·5
Phosphor bronze . ..	16·1	15·6	14·6	13·1	8·6

TABLE XXII

Material.	Values of Constants.	
	a.	b.
Copper	14·8	0·000014
Rolled yellow brass	24·1	0·000028
Rolled Delta metal	31·3	0·000041
Rolled Muntz metal . . .	14·7	0·000029
Cast gun-metal	12·5	0·000021
Cast brass	12·5	0·000024
Cast phosphor bronze	16·1	0·000026

When zinc is heated to between 400° C. and 600° C., it becomes very brittle, and often crumples up into small pieces when any attempt is made to work it.

* The phenomenon known as the "growth" of cast iron occurs at temperatures of 650° C. and above, and consists of a permanent expansion or elongation; and is believed to be due to internal oxidization caused by the penetration of oxidizing gases. Permanent "distortion" occurs at temperatures below 650° C. Automobile cylinders and super-heated steam cast-iron fittings experience "growth."

† For further information *vide* "The Heat Treatment of Cast Iron at Low Temperatures," J. E. Hurst; *Engineering,* July 4, 1919; and *The Autocar,* June 7.

The Failure of Materials—Tests to Destruction.

Theoretical Aspects.—The question of the mode of failure of materials is a very important one in engineering design, and it is therefore not surprising that considerable attention has been given to both the theoretical and experimental sides. The main problem connected with the subject of ultimate failure in ductile and brittle materials is to find whether the decisive factor is one of simple normal stress, strain, or of shear.

At the outset the failure of a material in tension can be definitely stated not to be due to any accompanying compressive stress, for the results of numerous experiments prove that no amount of compression will rupture a material, provided that the material is prevented from spreading laterally.

It is also fairly certain that either the maximum principal stress, principal strain, or maximum shearing stress, must be involved in the process of rupture.

There are three principal theories of failure based upon the above factors—namely:

1. That elastic failure occurs for a certain value of the maximum principal stress.
2. That it occurs for a certain value of the principal strain.
3. That it occurs or a certain value of the maximum shear stress.

It should be pointed out that the maximum shear stress depends upon the principal stress values.

The results of most experiments tend to confirm the belief that failure in the case of ductile materials such as iron and steel occurs by shear, and in brittle materials such as cast iron, concrete, or brick, by tension.

1. The maximum value of the principal stress, p, in the case of a material subjected to a tensile stress p_1 is given by—

$$p = \frac{p_1}{2} + \sqrt{\frac{p_1^2}{4} + q^2},$$

where q is the shearing stress.

2. The principal strain under these circumstances, on the St. Venant hypothesis, is given by—

$$e = \tfrac{1}{2}\cdot\frac{p_1}{E}\left(1-\frac{1}{m}\right)+\frac{1}{E}\sqrt{\frac{p_1^2}{4}+q^2}\left(1+\frac{1}{m}\right),$$

where $\frac{1}{m}$ is Poisson's ratio.

For the usual value of $\frac{1}{4}$ for Poisson's ratio—

$$e = \frac{1}{E}\left[0{\cdot}375p_1 + 1{\cdot}25\sqrt{\frac{p_1^2}{4}+q^2}\right]$$

The limiting case is obtained by putting $p_1 = 0$, which gives $p = \frac{5}{4}\cdot q$—that is to say, a shear stress equal to four-fifths of the tensile strength.

3. The shear stress theory* attributing failure to shear alone is based upon the relation—

$$q_1 = \sqrt{\frac{p_1^2}{4}+q^2},$$

where q_1 is the equivalent shear stress.

The limiting case is obtained by putting $q = 0$, which gives $p_1 = 2q_1$, or a shearing stress value equal to one half of the tensile strength.

There is also another theory, sometimes known as the Navier theory, which attempts to account for the fact that certain brittle materials fail by shear or sliding along definite planes inclined to the axis of push, not at the usually predicted 45°, but at a greater angle, $45° + \phi/2$, where ϕ is the angle of friction such that $\tan\phi = \mu$, the frictional coefficient. The results of compression tests upon brittle materials tend to support this view, as will be shown subsequently.

Nature of Actual Failure.

In the case of *ductile materials,* such as wrought iron, mild steel, rolled copper, and similar metals, failure in tension tests often consists of a reduction of area resultant upon the flow of metal, and a fracture at the least section, with the forma-

*Formulated by Guest and Fresca.

tion of a conical projection roughly of 45° side inclination, together with a conical recess, corresponding to the crater (Fig. 44, A).

In the case of *non-ductile materials,* failure occurs by a separation across a plane normal to the axis of pull, with little or no reduction of area or elongation. Cast iron and cast steel usually exhibit these properties. Semi-ductile materials yield by a combination of the two methods—namely, a normal yield by direct tension of the central core,

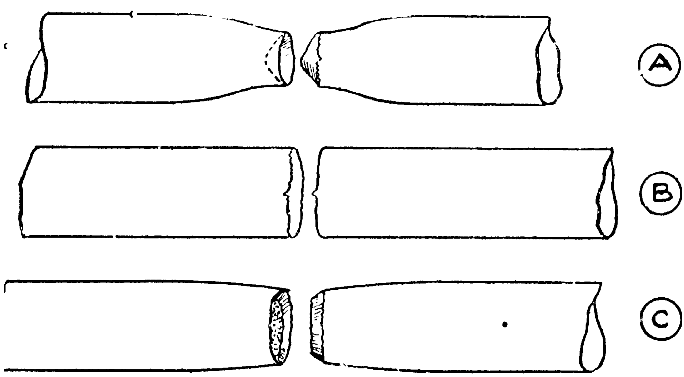


FIG. 44.

surrounded by a ring of metal failing by direct shearing, so as to leave a crater effect with a flat bottom, as shown in Diagram C, Fig. 44.

When a *ductile material* is tested in compression, if the length is more than four or five times the maximum width, there is no real failure, but a yielding by buckling, or secondary flexure, at a lower value of the stress than the true ultimate compressive stress. The failure of mild steel tubes under compressive load is an example of the case in point.

The longer the length, for a given cross-section, the lower will be the "buckling stress" value.*

When the length is less than three or four times the minimum width, the failure by compression is due to "bulging,"

* The subject of struts is considered upon p. 58.

or lateral expansion, due to the flowing out laterally of the material, as shown in Fig. 45.

The surfaces at which the load is applied become enlarged as the load increases, so that for this reason the actual stress is reduced for a given load. It follows that to continue the process of lateral flow, the load must be increased at a more rapid rate as the surfaces enlarge. For a perfectly ductile material there would be no limit to the amount of lateral bulging, and therefore no true ultimate compressive stress.

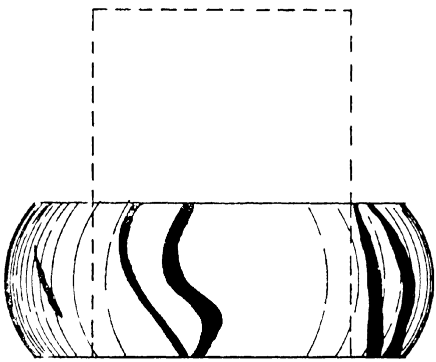


FIG. 45.—COMPRESSION FAILURE OF DUCTILE MATERIAL

In most ductile materials of commerce, such as mild steel, copper, and similar materials, there occurs a stage at which cracks appear upon the surface, as shown in Fig. 45, these cracks being accentuated in the case of fibrous or faulty materials.

Lateral yielding in the above cases is resisted by the frictional resistance between the surfaces of contact, which varies with the degree of roughness of the surfaces and with the compression load. For this reason the ends of a compression cylinder or specimen of a ductile material cannot flow laterally at the same rate as the central portions, so that a barrel-like shape is formed, as shown in Figs. 45 and 46. The latter figure illustrates the effects of compression stresses of 9000 pounds per square inch upon two equal cylinders of white-metal identical in composition, the centre specimen

being cast by the Eatonia process, whilst the other one was poured in the ordinary manner.

Brittle materials, such as cast iron, cement, and certain timbers, usually fail in compression by shearing and sliding along faces inclined to the axis of push. When the length of the test piece is not less than one and a half times the width, failure occurs by a simple shear fracture, diagonally, at an angle varying from 50° to 70° (for most materials) to the axis of push, so that the specimen is divided into two wedge-like parts.

For a shorter length to width ratio, failure occurs by the simultaneous shearing of the material over several planes, so that wedges or cones of the material forming the sides are

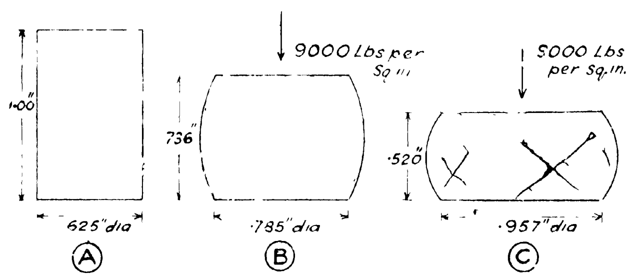


Fig. 46.—Failure of Plastic Material under Compression.

split off; and if the test is stopped at this stage, the remainder of the material, for very brittle substances, is left in the form of two cones of pyramids having as bases the surfaces of load application, and with contiguous apices, as shown in Fig. 47.

The breaking stress in this case is greater than in the preceding cases, and increases as the height is reduced, so that the plane of minimum resistance to shear cuts the faces at which the pressure is applied. Hodgkinson found that the ultimate compressive strength of cast-iron cylinders varied from 69·3 to 34·4 tons per square inch for height diameter ratios varying from ¼ to 7½ respectively.

When a smooth or polished specimen of mild steel or copper is tested in tension past the elastic limit, or when a tube of

a brittle* or semi-brittle material is tested in compression, lines appear upon the surface of the specimen, approximately spiral in form, and inclined at an angle of about 45° to the axis. Two systems of such lines mutually at right angles are usually found.

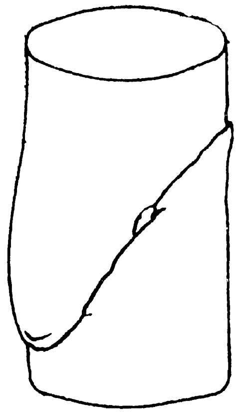


FIG. 47.

These lines, or cracks, which indicate local yielding or failure by shear, are known as Lüder's or Hartmann's lines. A typical example is shown in Fig. 48 for the case of a mild steel tube in compression.

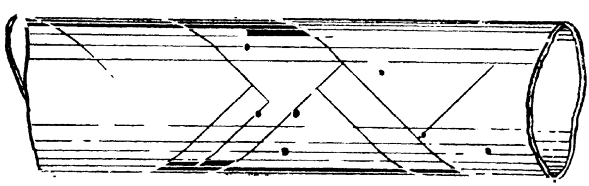


FIG. 48.—LUDER'S LINES ON STRESSED BRITTLE TUBE.

The angle of shear failure appears to be greater than 45° in most cases; thus, in the case of some cast-iron compression tests made by Hodgkinson the average inclination was

* Such as glass.

about 55°, whilst other tests upon bricks gave angles varying from 58° to 62°. The range of inclinations of these slip bands was observed by Hartmann to lie between 58° and 65° for various metals. These results certainly appear to support the explanation advanced by Navier.*

If the matter be considered from the point of view of the principal stresses and planes occurring, then, referring once again to the case of a simple normal stress considered on p. 19, it will be seen that although the maximum shearing stresses occur over planes inclined at 45° with the axis, yet the effect of the normal stresses upon these planes is to resist shearing, owing to the internal frictional resistance of the particles, so that sliding or yielding by shear occurs over planes inclined at a greater angle than 45°. The theoretical angle, as deduced from a consideration of the principal stresses, maximum shear stress, and the tangential frictional resistance of the particles, has been shown to be $45° + \frac{\phi}{2}$, where $\tan \phi = \mu$, the frictional coefficient.

Results of Microscopic Examination of the Metal.

The behaviour of the material under stress can be readily studied by examining the polished surface, which has also been lightly etched, under the microscope.

The normal structure† of a metal consists of a number of crystalline grains all joined together; each grain contains a definite arrangement or orientation of particles. The effect of a tensile stress is to elongate the crystals in the direction of pull.

The subject of the structure of metals under stress has been carefully investigated by Ewing and Rosenhain,‡ and the following extract§ may be of interest:

"Microscopic observations have demonstrated that the

* *Vide* p. 101. † Also see Chapter IV. for a fuller description.

‡ Phil. Trans. Roy. Soc., vol. cxciii., p. 279.

§ "The Strength of Materials," Proc. Roy. Soc., March 16 and May 18, 1899, p. 46, J. A. Ewing.

manner in which a metal yields when it takes any kind of permanent set is by slips occurring on 'gliding' surfaces within each of the crystalline grains. These slips show themselves on a polished surface by developing systems of parallel lines or narrow bands, each of which is a step caused by one portion of the grain slipping over the neighbouring portion. Two, three, and even four systems of slip lines may be traced when the metal is considerably strained. Plasticity results from these slips, although the elementary portions of the crystals retain their primitive form, and the crystalline structure of the metal as a whole is preserved. In some metals, in addition to simple slips, or motions of pure translation, there is a molecular rotation resulting from strain which gives rise to the production of 'twin' crystals. Apart from this, however, the occurrence of slips on three or more planes within each grain suffices to allow the grain to change its form to any extent as the process of straining proceeds."

The process of annealing an overstrained metal results in the loss of elongation, and reversion to the primitive arrangement of the crystals; the crystals will be coarse or fine according as the cooling after annealing is fast or slow.

The bands, or lines, known as the Luder lines are not actually the slip lines of the separate crystals, but are the integral effects or results of the component crystalline slips.

Shearing Strength of Metals.

The resistance to shearing is invariably less than to direct tension or compression in the case of metals,* it also varies in the case of rolled plates according to the direction of rolling, being less when the planes of shearing lie along this direction.

In the case of some Bessemer steel boiler plate tested by Bauschinger, it was found that the shearing strengths across the directions of rolling were 26·45 and 27·35 tons per square inch, whilst in the rolling direction they were 21·45 and 22·90 tons per square inch respectively.

* See Tables in Appendix II.

The shearing strength of steels varies from about 0·65 to 0·80 of the tensile strength; thus, in the case of mild steel plate of 26·9 tons per square inch tensile strength, and 34·7 per cent. elongation, the shearing strength was 21·0 tons per square inch. For wrought iron the shearing strength varies from about 15 to 20 tons per square inch across the grain.

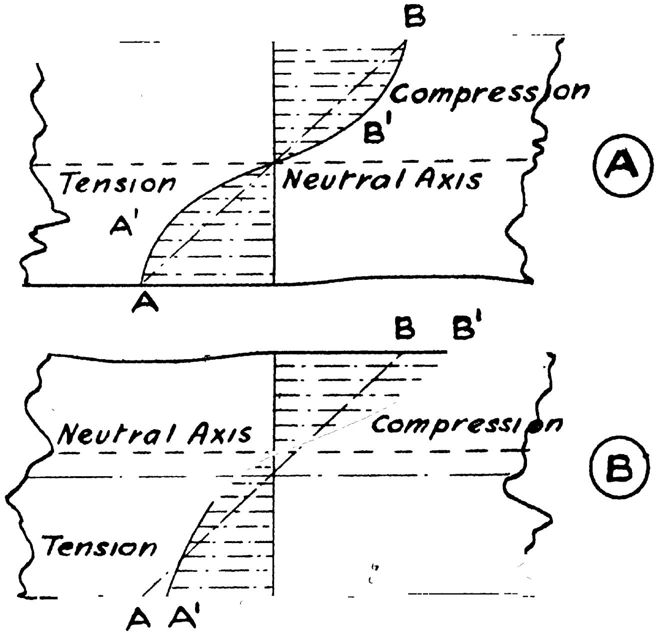


FIG. 49.—STRESS DISTRIBUTION IN BEAM SECTION A, DUCTILE MATERIAL; B, NON DUCTILE MATERIAL.

For crucible steel (0·8 carbon) the tensile and shear strengths are 60 and 38 tons per square inch respectively.

The resistance to shearing of cast iron is imperfectly known, some experiments finding a lower value than for the tensile strength, whilst some have found a greater value. Izod*

* Proc. Inst. Mech. Engineers, 1905.

found that the shearing strength varied from 1·10 to 1·50 times the tensile strength.

The shearing strength of rolled phosphor bronze varies from 50,000 to 60,000 pounds per square inch.

Failure of Beams.

The ordinary engineers' bending theory discussed in Chapter I. (p. 34) is based upon certain assumptions, one of which is that the stress and strain of the material of the beam must obey Hooke's law—namely, that the two are directly proportional. This relation only holds for certain ductile materials, up to the elastic limit, and does not hold for non-ductile materials such as cast iron, very hard steel, and timber.

The results obtained, on these assumptions, therefore, can only apply to cases of bending within the elastic limits for ductile materials.

Beyond the elastic limit, the distribution of normal stress over the cross-section of a beam, instead of being represented by the dotted straight line AB shown in Fig 49, A, is that shown by the full line A^1B^1. Diagram A represents the case of a ductile material, such as mild steel, in which the elastic limit in tension is the same as in compression. Diagram B refers to the case of a non-ductile material, such as cast iron, which is considerably stronger in compression and which does not obey Hooke's law; in this case the neutral axis approaches the compression side.

In order to predict the breaking stress, in the case of beams tested to fracture, the law of behaviour of the material in compression and tension beyond the elastic limit must be known.

The ordinary beam theory gives the value of the maximum stress p at any section, at which the B.M. is M, as

$$p = \frac{My}{I},$$

where y = distance of extreme layer of fibre from the neutral axis, and I is the moment of inertia of the section about the neutral axis.

If, now, the value of the B.M. causing fracture be denoted by M_1, then the imaginary stress p_1 caused by this B.M. is often calculated from the above formula—viz.:

$$p_1 = \frac{M_1 \cdot y}{I}.$$

It has already been pointed out that the ordinary beam theory results do not apply to cases of bending beyond the elastic limits, but this method of expressing the ultimate strength of beams is rather convenient, if incorrect.

The stress p_1 is known as the *Bending Stress*, or *Strength*. or the *Modulus of Rupture.*

Its value is in general appreciably higher than the ultimate strength in tension, and for the same material it varies with the shape of the section. In expressing bending strengths it is usual, therefore, to specify the shape of the section; usually it is rectangular.

In the case of an I beam, in which the web area is small compared with that of each flange, the stress over each flange is practically uniform, and for a plastic material like wrought iron or mild steel, in which the tensile and compressive strengths are equal, the bending strength will be very nearly equal to either of these.

For rectangular beams it is probable that the stress distribution at fracture is nearly uniform over each half of the section, in which case the moment of resistance $M_1 = \frac{1}{4}p\ ba^2$, whereas upon the ordinary beam theory its value should be $M_1 = \frac{1}{6}p\ ba^2$. The value of the bending strength on this assumption is $1\frac{1}{2}$ times the ultimate tensile or compressive strength; actually it is very nearly this value.

The relation between the tensile strength f_t and the modulus of rupture p_1 for cast iron (of the same composition) is given by Bach as—

$$p_1 = k \cdot f_t \sqrt{\frac{y}{z}},$$

where y = distance from neutral axis to the tension edge;

z = strength modulus of section.

The value of the constant k varies from 1·2 for rectangular sections and I sections, to about 1·33 for curved contour sections.

It has been found that for cast iron the value of p_1 is greater for smaller rectangular sections than for larger ones of the same proportions; thus, the respective values for p_1 for square cast-iron beams of sides 1, 2, and 3 inches, were found by

TABLE XXIII

MODULUS OF RUPTURE VALUES.

Material.	*Ultimate Strength in Tons per Square Inch.*		
	Tension.	*Bending.*	*Compression.*
Cast iron—			
1 inch × 1 inch deep	7–13	20·41	50–70
1 inch × 2 inches deep ..		22·60	
1 inch × 3 inches deep ..		15·45	
Circular 2 inches diameter ..		24·28	
Mild steel—			
1 inch × 1 inch	0·28	34·00	—
Gun-metal—			
96·3 copper; 3·7 tin	14·29	14·83	—
80 copper; 20 tin	14·72	25·32	—
Brass—			
82·5 copper; 17·5 zinc ..	14·55	10·35	—
60 copper; 40 zinc	17·40	18·33	—
45 copper; 55 zinc	21·63	10·78	

D. K. Clark to be 20·41, 14·43, and 12·92 tons per square inch respectively.

The results of tests* upon differently proportioned rectangular sections showed that wide and shallow sections give a higher value for p_1 than narrow and deep sections, and that the circular section has a higher p_1 value than a rectangular.

Values of the bending† and tensile strengths of typical materials are given in Table XXIII.

* "The Testing of Materials," p. 292, C. A. Unwin.

† Values for different timbers will be found in Vol. II. of this work.

Practical Bending Tests.

A common test for cast iron is to cast a number of bars of the particular material, the dimensions when machined being 3 feet 6 inches × 2 inches × 1 inch, and to place each bar upon knife-edge supports 3 feet apart, with the 2-inch side vertical; the bar is then loaded at the centre until it breaks. The usual breaking load specified for a good quality of iron for castings is from 1·3 to 1·9 tons, and the deflection just before fracture should lie between 0·3 and 0·5 inch.

The bend test usually specified for mild steel bar* is that a rod of from $\frac{1}{2}$ inch to $\frac{7}{8}$ inch diameter should stand bending over through 180° to an internal radius equal to the diameter of the bar. The same test is sometimes specified for standard steel bars of up to 50 tons ultimate strength for aeronautical work.

Steel plate is usually tested for bending by doubling it over flat upon itself in any direction of the plate, and hammering or pressing it double.

For alloy steel plates this method is modified somewhat by specifying a maximum internal radius, after bending double, equal to the plate thickness.

The International Aircraft Standard Bend Test Specification.

Bend Test.—(*d*) The specimens shall be bent cold in the bend test.

(*e*) *Bars.*—Bars will be bent around a pin of radius equal to the bar diameter or thickness until the sides are parallel; unless otherwise noted, the bar must withstand such bending without developing cracks or signs of failure.

(*f*) *Sheets.*—The test comprises two distinct operations, both of which are performed by the use of a press, or, in the absence of this, by using a knife-edge and hammer. First, the strip is placed in position *AB* (Fig. 50) on block having a V-shaped groove. The knife-edge is placed as shown, and pressure is applied by means of either press or hammer until

* Tensile strength from 30 to 37 tons per square inch.

the test specimen assumes the shape A^1B^1. After this block is removed the bending is finished as indicated in Fig. 51, with or without the interposition of a spacer. The spread of the ends of the test piece varies with the quality and thickness of the sheets. The specimens must be bent as indicated without breaking, and after test shall not show hair lines, cracks, or other defects.

Other Bending Tests.—Mild steel tubing is often specified to be of such a quality as to withstand bending over through 180° and hammering flat without splitting or showing flaws.

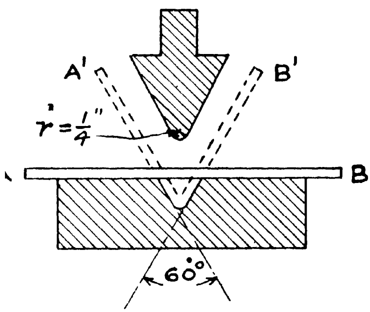


FIG. 50.

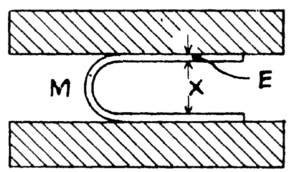


FIG. 51.

Brass and copper tubes for withstanding hydraulic pressure up to 300 pounds per square inch are tested by sawing longitudinally one side of a piece of length equal to at least 2 diameters, and then bending the metal inside-out until it is bent double upon itself.

Another test is to fill a piece of the annealed tube, of length equal to not more than 15 diameters, with resin, and to bend this tube around in a circle until the extremities touch. No cracks or flaws must develop in either case

Still another test is to place the tube upon two supports at a distance apart equal to 10 diameters, and to load the tube centrally until the deflection is equal to $1\frac{1}{2}$ diameters; no defects should show after this test.

Rafwires and Wing Bracing Wires.

It is usual to specify a bend test, which necessitates bending through 180° until the internal radius of the bend is equal to the minimum width or diameter of the wire, as the case may be. No cracks should show on the surface.

Stranded Steel Cable.

The flexible type as used in aircraft work should be capable of bending around a rod equal in diameter to its own a large number of times, without any of the strands fracturing.

Malleable Bronzes (such as Delta Metal).

These materials, which can be forged, must be able to withstand, without cracking, the test of a circular bar being

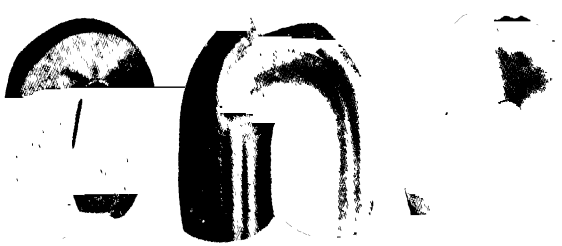


FIG. 52.—COLD BEND TESTS UPON NICKEL-CHROME STEEL.

bent double (*i.e.*, through 180°) until the internal bend radius is equal to from $1\frac{1}{2}$ to 2 times the diameter of the bar.

Fig. 52 shows some photographic reproductions of cold-bending tests upon nickel-chrome steel* having an elastic limit of 40 tons per square inch, and a breaking strength of 50 tons per square inch, with a 20 per cent. elongation on 2 inches and a 50 per cent. reduction of area.

The left-hand specimen was a 1-inch square bar, and the centre one a $1\frac{1}{2}$-inch round bar, having originally a deep

* Made by Messrs. Vickers, Ltd.

notch upon the tension side. The specimens were bent under a hydraulic press.

Fig. 53 is a photographic reproduction* of bend tests upon a case-hardened nickel steel of two grades of hardness—A and B—and a case-hardened mild steel C.

The steel in A was case-hardened in the ordinary way, but was quenched in cold water. It is stated that the skin was

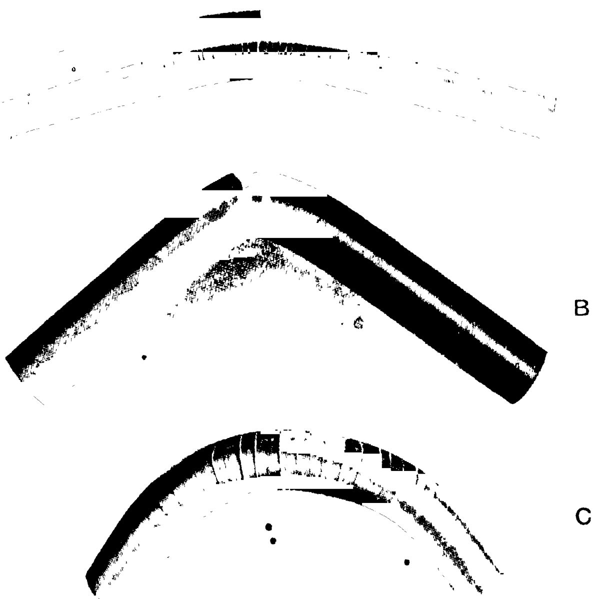


Fig. 53.—Results of Bending Tests upon Case-Hardened Mild and Nickel Steels.

so hard that it readily scratched glass. The core had an elastic limit of 65 tons per square inch, and an ultimate strength of 80 tons per square inch. Its smaller degree of elongation is apparent by the relatively smaller bending angle before fracture.

The same steel is shown in B, but quenched in boiling water.

* Upon steels made by Messrs. Vickers, Ltd.

The skin is stated to be hard enough to just scratch glass, and to be too hard to file. The ultimate strength of the core is given as 37 tons per square inch.

The mild steel bar shown in C was $\frac{7}{8}$ inch in diameter, and had a glass hard skin. Tensile test results of the material of the core gave an elastic limit of 22 to 25 tons per square inch, and an ultimate strength of 35 to 40 tons per square inch, with an elongation varying from 33 to 30 per cent., and a reduction of area of from 70 to 60 per cent. The fracture was fibrous, and was coarser than that of the steel in the preceding examples.

The Torsion Test.

It is a matter of some surprise that the torsion-test method is not more widely adopted, in view of the fact that a large number of materials are employed for rotating parts and parts subjected to shear; several of the large automobile steel manufacturers are beginning to recognize the value of the torsion test, and are subjecting their materials to it, as a pass test.

In torsion tests the strength of the material under shearing action is that chiefly concerned, and it may be regarded as a ready means for observing the shear strength and modulus of rigidity of the material.

When a circular rod of a plastic material is subjected to a torque of comparatively small amount, the shear strain at any part is proportional to the torque or to the shear stress, and it is a maximum at the periphery and zero at the centre. Within the elastic limits in shear, the stress is almost directly proportional to the strain, but beyond the elastic limit the specimen will take a permanent set, or twist, when the torque is removed (which may, however, be removed by annealing).

When the torque is continued, in the case of a plastic material it is found that when the maximum shear stress is reached on the surface, which would cause breaking, the specimen does not suddenly shear, but that fracture only

occurs when the maximum shear stress becomes practically uniform over the whole section: it does not, of course, increase any more at the surface.

The value of the shear stress calculated from the breaking torque value is always higher than the ordinary value as found by more direct tests; this, as in the case of stresses calculated for beams at their breaking-load values, is due to the non-application of the formulæ based upon the ordinary assumptions of stress and strain proportionality.

Torsion Test Results.—When a cylindrical specimen is gripped in the torsion-testing machine at the one end and twisted at the other, it is found that an initially straight longitudinal line upon the surface becomes spiral or helical as the torque is increased, and that the specimen progressively shortens in length and increases in cross-section. For plastic materials such as iron and steel, in the shape of cylindrical

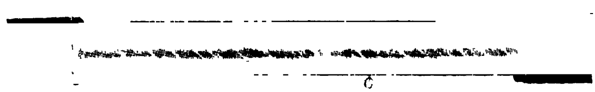


FIG. 54.—TORSION-TEST SPECIMEN. CASE-HARDENED NICKEL STEEL.

rods of length equal to about eight diameters, the specimen will require between $5\frac{1}{2}$ and 8 complete revolutions before fracturing. For high-carbon and alloy steels the number of twists varies from $1\frac{1}{2}$ to 4.

For *cast iron* the torque T_m which will break a circular bar can be calculated from the following empirical relation:

$$T_m = 0{\cdot}196 \; q_m \cdot d^3,$$

where q_m = the equivalent shearing stress, d = diameter or coefficient of torsional stress.

The value of this coefficient varies from about 13 tons per square inch, in the case of the softest grey iron, up to about 24 tons per square inch for the hardest white iron, being about 18 for medium grades.

The following tables (Nos. XXIV. and XXV.) show some torsion tests to destruction results for iron and steels.

Table XXIV. refers to some of the results of Platt and Hayward's experiments.*

TABLE XXIV.

TORSIONAL AND SHEAR STRENGTH OF STEEL AND IRON.

Material.	*Elastic Limit in Tons per Square Inch.*	*Coefficient of Torsional Stress at Fracture in Tons per Square Inch.*	*No. of Revolutions in 9-Inch Length to Fracture.*	*Coefficient of Rigidity in Tons per Square Inch.*	*Ultimate Tensile Strength in Tons per Square Inch.*	*Ultimate Shearing Strength from Shearing Tests in Tons per Square Inch.*
Wrought iron, crown best	8·99	25·2	8·90	5714	21·60	18·76
Bessemer steel ..	20·28	44·62	3·84	5750	52·20	35·21
Crucible steel ..	19·36	42·30	4·36	6098	52·16	33·30
Rivet steel ..	10·20	29·85	7·85	5834	28·40	23·00
Steel from casting	10·40	34·70	4·15	5882	38·04	27·60
Siemens - Martin steel	10·16	28·13	9·92	5981	25·75	20·94

TABLE XXV.

RESULTS OF TORSIONAL TESTS UPON ALLOY STEELS.
(Messrs. Vickers, Ltd.)

Material.	*Tensile Test.*				*Torsion Test.*			
					Calculated Shearing Stress.		*Final Twist.*	
	Elastic Limit.	*Ultimate Strength.*	*Elongation per Cent.*	*Reduction of Area per Cent.*	*Elastic Limit.*	*Maximum.*	*Angle °*	*Revolutions*
Carbon steel (axle)	24·8	39·6	30·0	63·6	17·2	39·2	1405°	3·90
Nickel steel	33·2	44·4	25·0	65·8	23·2	40·5	1474°	4·09
Nickel-chrome steel	45·6	58·0	19·5	63·6	33·5	49·2	1252°	4·48

Note.—The torsion specimens measured 8 inches long by 1 inch diameter. All stresses are given in tons per square inch.

* Proc. Inst. Civil Engineers, vol. xc., p. 382.

Repeated Stresses.

Hitherto only the steady or static stresses have been considered; it next remains to consider the effect of stresses caused by loads which fluctuate in value between certain specified limits, frequently. Such stresses occur in numerous cases in engineering practice, and their effects are quite different from those of simple static stresses of the same amount. In the following notes stresses which are of the same sign—that is, either of tension or of compression—but which fluctuate in value, will be termed "varying" stresses, whilst those which alternate from tension (or positive) through zero to compression (or negative), or *vice versa*, frequently, will be termed "reversed" stresses. The term "alternate" will be employed to denote both of these stresses collectively.

If the stress limits lie well within the elastic limits the stress variations may proceed for very long periods; for example, the hair spring of a watch is alternately in tension and compression at the rate of about 150 million alternations per annum.

On the other hand, if a piece of metal strip or bar be bent backwards or forwards a few times so that stresses are outside the elastic limits, it will fracture in a very short time.

It has been found that metals which are subjected to frequently alternating stresses will fracture at a much lower value than their ordinary statical stress, and that the material will fracture sooner for a given range of reversed stress than for the same range of varying stress.

Further, the effect upon the elastic limit of a frequently varying stress of a maximum amount which does not exceed the original statical elastic limit is to raise same; the effect of a reversed stress is to lower the elastic limit.

Extensive researches upon alternating stress effects, extending over a period of twelve years, were made by Wohler,* the results of which were published in 1870.

* "Die Festigkeits-Versuche mit Eisen und Stahl." Berlin, 1870. Also in *Engineering*, vol. xi., 1871.

These tests were made in machines of different kinds in which the specimens could be subjected to direct tension between any predetermined limits, to repeated bending in one or in opposite directions, or to repeated torque of opposite signs.

One type of machine which has since been employed in later alternating stress tests is similar to that shown upon p. 212; this machine was used for alternating bending stresses, so that the material was alternately in tension and compression once every revolution of the driving shaft.

The general result of these researches (since repeated and confirmed by other experimenters) was to show that the resistance to fracture or the safety of any engineering structure under alternating stresses depends primarily upon *the range of variation of the stress,* and upon the number of repetitions of same.

Also, that reversed stresses well within the elastic limits will ultimately cause fracture if repeated for a sufficiently large number of times.

Furthermore, Wohler showed that in general the smaller the range of stress, and the lower the value of the maximum alternating stress, the greater the number of repetitions of stress it will stand before fracturing.

Below a certain limit of stress range, the material will stand an indefinite number of stress repetitions before reversal.

Thus, in the case of a certain grade of mild steel it was found that when the tensile stress varied from zero to 30 tons per square inch at a given rate of loading, the material fractured. When the range was from zero to 25 tons per square inch, half a million reversals, at the same rate of loading as before, were sufficient to cause fracture. From zero to 23 tons per square inch, a million reversals caused fracture; from zero to 20 tons per square inch, 4½ million reversals were necessary.

When the stress varied from zero to 15 tons per square inch frequently, it was found the "limiting range of stress"

was reached at which an indefinitely large number of reversals would be necessary to cause fracture.*

It has been found that alloy and high-carbon steels withstand a greater number of stress repetitions of the same range than mild steel or wrought iron, and that they possess a higher limiting range of stress.

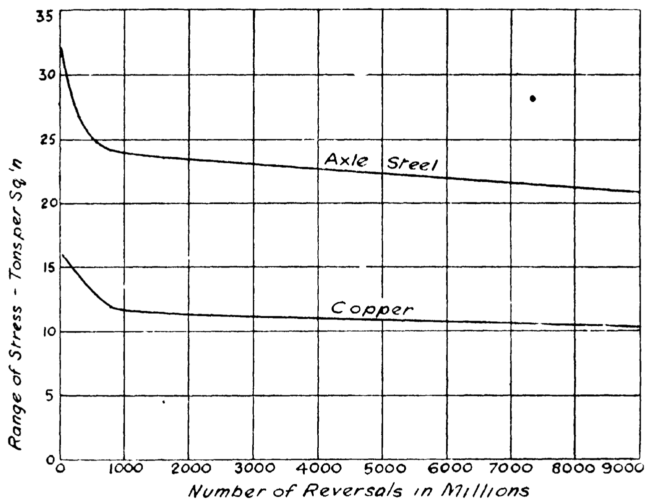


FIG. 55.

The results given in Table XXVI., and which are represented graphically in Fig. 55, show the relations between the range of stress and the number of stress repetitions for the materials indicated.

The effect of "reversed" stresses as compared with "varying" stresses is best shown by considering some of the more reliable experimental results,† such as those given in Table XXVII. It will be seen at once that for a given number of

* Later researches point to the conclusion that there is a definite but very small change in the structure of the metal, even for very small ranges of stress, and that no metal would stand an infinite number of variations.

† *Vide* Unwin's "Testing of the Materials of Construction."

TABLE XXVI.

RELATION BETWEEN STRESS REPETITIONS AND STRESS RANGE.
(Wöhler.)
(Rotating Bars in Reversed Bending.)

Material.	*Stress in Tons per Square Inch.*		*Range of Stress in Tons per Square Inch.*	*No. of Repetitions before Fracture.*
	Maximum.	*Minimum.*		
Axle steel ..	+ 16·3	− 16·3	32·6	51,240
	15·3	15·3	30·6	72,940
	14·3	14·3	28·6	205,800
	13·4	13·4	26·8	278,740
	12·4	12·4	24·8	564,900
	11·5	11·5	23·0	3,275,860
	10·5	10·5	21·0	8,660,000*
Copper rod ..	+ 7·64	− 7·64	15·28	30,875
	7·64	7·64	15·28	67,725
	6·69	6·69	13·38	480,700
	6·21	6·21	12·42	663,100
	5·97	5·97	11·94	798,000
	5·73	5·73	11·46	2,834,325
	4·78	4·78	9·56	19,327,460

stress repetitions causing fracture the range of reversed stress may be about the same in each case, but that the maximum stress for a given range is considerably lower for the case of reversed stresses.

Another feature confirmed by the tabular data is that of the greater range of stress which materials of higher tensile strength will withstand; thus, in the case of the wrought-iron tests the maximum range of reversed stresses was 14·3 for a tensile strength of 22·8 tons per square inch, whereas in the case of Krupp's axle steel this range was 28·1 for a tensile strength of 52 tons per square inch. Fig. 56 illustrates graphically the relation between the limiting stresses, the stress range for static, varying, and reversed stresses, and the number of reversals to just fracture, for mild steel.

* Not broken.

In the case of the results given for untempered spring steel (Table XXVII.) it will be seen that the range of varying stress progressively diminishes as the maximum value of the stress attained increases, the limiting value being that of zero range for the ultimate statical tensile strength.

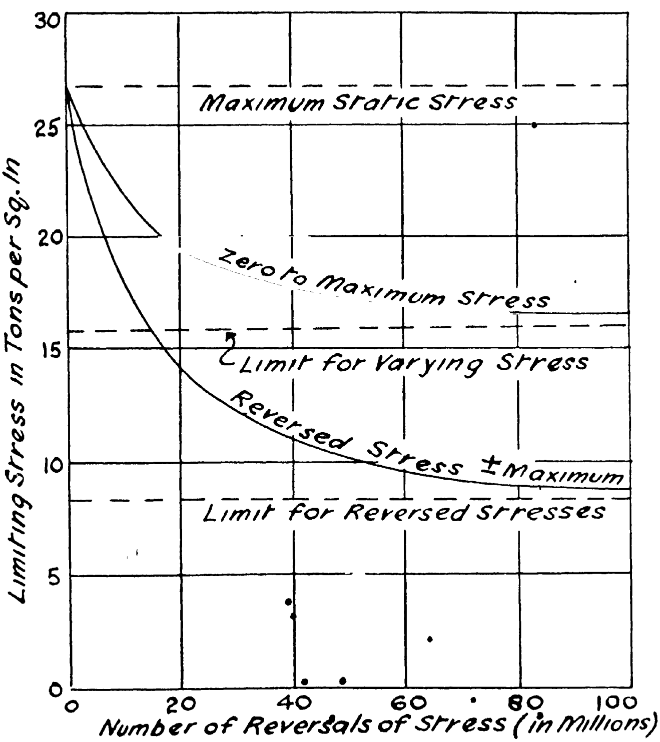


FIG. 56.—STRENGTH OF MILD STEEL UNDER ALTERNATE STRESSES.

It should be emphasized that the above results refer to what may be termed the varying and reversed stress limits for a given endurance before fracture—namely, of at least 2 or 3 million stress-cycle repetitions.

TABLE XXVII.

RESULTS OF REPEATED STRESS TESTS.* (Wöhler.)

Material.	*Minimum Stress.*	*Maximum Stress.*	*Range of Stress.*	*Statical Tensile Strength.*	*Authority.*
	Tons	*per*	*Square*	*Inch.*	
Wrought-iron plate..	0	13·1	13·1	22·8	Bauschinger.
	11·4	19·2	7·8	22·8	,,
	−7·15	+7·15	14·3	22·8	,,
Bessemer steel ..	0	15·7	15·7	28·6	Bauschinger.
	14·3	23·8	9·5	28·6	,,
	−8·5	+8·5	17·10	28·6	,,
Axle steel	0	18·4	18·4	39·0	Bauschinger.
	19·5	30·85	11·35	39·0	,,
	−9·7	+9·7	19·4	39·0	,,
Krupp's axle steel ..	0	26·5	26·5	52·0	Wöhler.
	17·5	37·75	20·25	52·0	,,
	−14·05	+14·05	28·10	52·0	,,
Spring steel (not tempered)	0	25·5	25·5	57·5	Wohler.
	12·5	35·0	22·5	57·5	,,
	20·0	40 0	20·0	57·5	,,
	30·0	45·0	15·0	57·5	,,

Note.—The above results refer to cases in which the material withstood at least 2 or 3 million repetitions before breaking.

Effect of Rate of Loading.—It has been found† that the rate of load or stress repetition may vary from zero to about 700 or 800 alternations per minute without appreciably affecting the results. Wöhler's tests were made at 60 alternations per minute. Messrs. Eden, Cunningham, and Rose‡ found no effect upon the limiting range of stress between 250 and 1300 revolutions per minute. On the other hand, Reynolds and Smith§ found a diminution in the stress range of about 30 per cent. for an increase in the alternations from 1600 to 2400 per minute in the case of mild steel.

* For more extensive results refer to Unwin's "Testing of Materials."

† Stanton and Bairstow, Proc. Inst. Civil Engineers, vol. clxvi.

‡ "Endurance of Metals," Proc. Inst. Mech. Engineers, 1911.

§ Phil. Trans. Roy. Soc., 1902, p. 265.

It was also shown that a high-tensile steel such as cast steel of 58 tons per square inch did not have any higher stress range at these high speeds than 26-ton mild steel.

Formulæ for Stresses due to Repeated Loading.

The published results of Wöhler's alternating stress tests have been embodied in the following formula, due to Gerber:

Calling k_{max} the breaking strength of the material for a repeated load giving stresses ranging from k_{max} and $\pm\ k_{min}$ for an indefinitely great number of alternations, then the stress range

$$\Delta = k_{max} \pm k_{min},$$

where $\pm\ k_{min}$ corresponds to stresses of the opposite kinds to k_{max} and k_{min} to the same type of stress.

The stress range Δ is then always positive in value. If K is the statical breaking strength of the material, then

$$k_{max} = \frac{\Delta}{2} + \sqrt{K^2 - n\Delta K}$$

expresses the results of Wohler's tests, where n is a constant whose value depends upon the type of material.

For wrought iron and mild steel $n = 1{\cdot}5$.

For hard steel .. .. .. $n = 2{\cdot}0$

In Table XXVIII. the formulæ, deduced from the one above, are given for certain special cases of practical interest.

By substituting the values of n previously given for ductile materials, the reversed stress limit (k_{max}) works out at K/3—*i.e.*, the working stress limits must not exceed from $-\frac{K}{3}$ to $+\frac{K}{3}$.

For varying stresses from zero to k_{max}, the value of k_{max} works out at 0·61 K, so that the working limits of stress for stresses varying frequently from zero to a maximum should not exceed 0·61 of the statical ultimate strength.

For hard and brittle steels, the corresponding reversed stress limits are from $-\frac{K}{4}$ to $+\frac{K}{4}$, and for varying stress from 0 to 0·472 K.

TABLE XXVIII.

FORMULÆ FOR VARIOUS KINDS OF REPEATED LOADING STRESSES. (Unwin.)

Type of Stress Variation.	*Stress Range* Δ.	*Formula for Maximum Stress causing Fracture for an Infinite Number of Load Repetitions.*
Steady stress k_{max} only	zero	$k_{max} = K$
Tension, from 0 to k_{max}	k_{max}	$k_{max} = 2(\sqrt{n^2+1} - n)K$
Tension, from 0 to $\frac{k_{max}}{2}$	$\frac{1}{2}k_{max}$	$k_{max} = \frac{4}{3}\left(\sqrt{\frac{n^2}{9}+1} - \frac{n}{3}\right)K$
Tension, from $\frac{k_{max}}{2}$ to k_{max}	$\frac{1}{2}k_{max}$	$k_{max} =$ ditto.
From $-\frac{k_{max}}{2}$ to $+\frac{k_{max}}{2}$	k_{max}	$k_{max} = 2(\sqrt{n^2+1} - n)K$
From $-k_{max}$ to $+k_{max}$	$2k_{max}$	$k_{max} = \frac{K}{2n}$

The Launhardt-Weyrauch Formula.—This empirical formula expresses the limiting value of k_{max} for both varying and reversed stresses, and gives results which agree fairly well with the observed ones.

$$\text{Thus, } f_{max} = \tfrac{2}{3}K\left(1 + \tfrac{1}{2}\frac{f_{min}}{f_{max}}\right) \text{ for mild steel.}$$

This formula* gives a reversed stress limit of from $-\frac{K}{3}$ to $+\frac{K}{3}$, and a varying stress limit of from 0 to $\frac{K}{2}$.

The diagram shown in Fig. 57 expresses the results of the above formula graphically, and enables the limiting value of the maximum stress f_{max} to be read off for any given type of stress variation. For example, for a stress varying from a negative value denoted to scale by *oc*, the range of stress is represented by *cot*, and the safe maximum stress by *ot*.

For a varying stress commencing from any initial value o_1t_1, the permissible range is given by t_1t_2, and the maximum allowable stress by o_1t_2.

* In deducing these values, the sign of f_m must be taken as being negative.

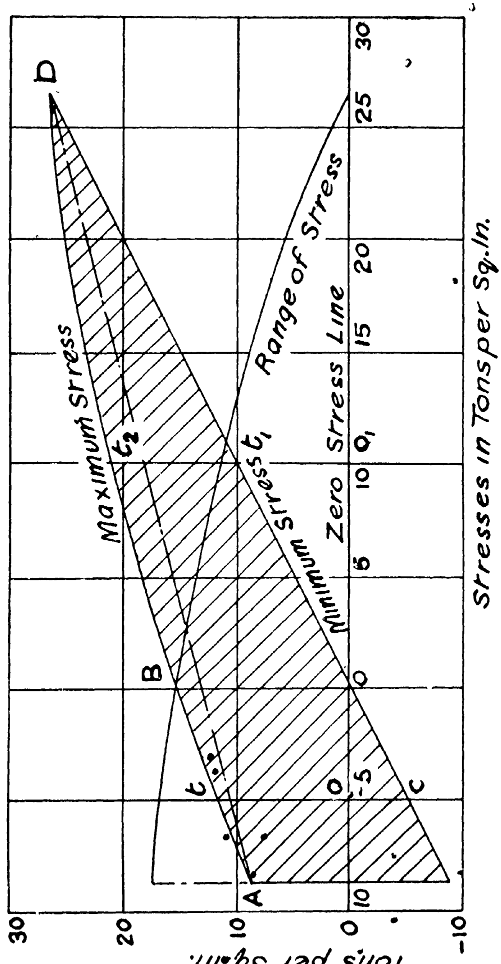


FIG. 57.

These stresses are the limiting values which will withstand an almost indefinite number of repetitions at a rate not exceeding a few hundred per minute. The maximum stress

curve ABD is often, as in the above formula, replaced by the straight line AD. Fig. 57 also shows the "range of stress" curve for different values of the maximum stress (abscissæ).

Fatigue.

When a material suffers fracture owing to repeated stresses of varying amounts, it is said to suffer "fatigue" or weakening.

It has been a popular notion for a long time that the effect of repeated stresses or of shocks* is to alter the molecular structure of the metal, and to render it "crystalline" or brittle. The structure of a metal is necessarily crystalline always, but the effect of an ordinary tensile fracture is that the crystals become elongated in the direction of the pull, so that they collectively present a fibrous appearance, whereas in the case of a fatigue fracture (which invariably occurs without local deformation even in ductile materials) the crystals are broken through without being elongated appreciably, so that collectively the fracture appears to the eye crystalline.

The first visible effect of fatigue is in the production of slip bands upon odd crystals, even for stresses within the elastic limits; the next change consists of a multiplying slip-band effect, in which more crystals are affected and broader bands develop, and also the edges roughen and become blurred. These slip bands next develop into cracks which spread from crystal to crystal until fracture as a whole occurs. It has been noticed that when a crack or flaw is present, the effect of fatigue is to spread from this place over the rest of the surface.

Impact or Shock Stresses.

In the preceding cases of repeated stresses the loadings have been more or less gradual, although reference* has been made to cases of repetition rates up to 2400 per minute; it is

* See p. 124.

possible that very rapid reversals and alternations of loading produce the same effects as those of impact or shock.

There is, however, a difference between the effects of gradually applied and suddenly applied stresses, for the general effect of a shock is to tend to destroy the plasticity of the material and to produce a certain local hardening effect; the net effect of repeated shock is a gradual falling off in the strength of the material and, if the intensity of the stress produced exceeds a certain limit, an ultimate rupture.

The subject of shock or impact stresses is of very high importance in automobile and aircraft practice; for example, when a motor-car is travelling over a bad road a series of impacts are given by the road to the wheels; these are partly absorbed or expended in deformation of the springs and tyres, but are also transmitted to the chassis and body members as modified shocks, and the car members must be designed to withstand such shocks. Even so, cases frequently occur of bolts, pins, and other members fracturing after a certain period of wear.

In the case of aeroplanes, owing to the limiting weight allowable for the undercarriage springing, part of the taxi-ing and landing shock is transmitted to the framework of the undercarriage, wheel axle and components, and fuselage. Again, the cylinder and piston, gudgeon pin, connecting rod, crank-shaft, valves, and tappet mechanism of petrol engines are subjected to explosion and operating shocks, and the design must allow for shock stresses occurring repeatedly. All parts subject to repeated shock or impact require higher factors of safety than for gradually repeated or static stresses of the same kind.

When a weight W is allowed to fall suddenly upon a vertical bar or rod, as shown in Fig. 58, so as to produce a tensile stress effect, the *strain* produced is *double* that which would be produced by the same load gradually applied; and, similarly, the *maximum stress* ot a sudden load or shock will be *double* that of a gradual load of the same amount.

If the stress produced lies within the elastic limit, the bar will execute a number of longitudinal vibrations similar to a spring, and these will gradually die away in time.

If, however, the stress produced is just greater than the elastic limit, then the material becomes slightly elongated permanently. Another way of considering the effect of shock is from the energy standpoint, for the kinetic energy of the blow (as in the case of a falling weight) must be used up in stretching the specimen and its supports. If the latter be assumed rigid, the whole of the shock energy is utilized in

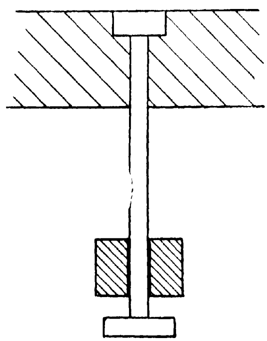


FIG. 58.

stretching the specimen; if now this shock energy be greater than the amount of work capable of being used up in elastic strain, the elastic limit will be exceeded, and a hardening effect upon the material will occur. Each succeeding shock of the same amount will in turn cause a corresponding hardening tendency, so that there will be a gradual deterioration of the material owing to its loss of plasticity or power of elongation. Such effects occur in the cases of crane chains, hawser and wire ropes, subject to live loads; these, in practice, are found to gradually weaken, and to ultimately break at a comparatively low load value, which would hitherto have been considered quite safe.

The instantaneous stress produced by a live load W, in

the case of a member carrying a dead or steady load W_1 of the same kind, is given by—

$$p_1 = \frac{W + W_1}{A} + \frac{W}{A},$$

where A = cross-sectional area of member.

Or, the instantaneous stress produced is equal to the sum of the live and dead load stresses, considered as an equivalent dead load, plus the "change in load" stress considered as a dead load.

The gradual deterioration in a material subjected to shocks is often termed "fatigue," for the fractures which occur under these circumstances are similar to that of brittle or non-ductile materials—namely, without any appreciable elongation, the application of the term "fatigue" in such cases is probably more justifiable than when used in connexion with deterioration under repeated stresses In either case, however, the ultimate effects bear a resemblance, and the process of annealing can be equally well applied to fatigued materials which are not too badly weakened, even although the elastic limit has been exceeded.

Working Stresses in Materials—Factors of Safety.

The whole subject of engineering design is largely governed by considerations of the maximum allowable stresses. In many cases the proportions of members under stress cannot be directly estimated, and often the proportions of the loads borne by members cannot be accurately computed; in such cases the dictates of experience and of experiment must decide the actual proportions.

In the majority of cases occurring in design work, however, it is possible to estimate the loads coming upon the members of an engine, machine, or structure, and the proportioning of these members for successfully withstanding their loads for long periods can be readily decided from a knowledge of the properties of the material under the particular type of load application—*i.e.*, whether the stress produced is a static, varying, reversed, or impact one.

The final dimensions are not always entirely fixed by such considerations, although these are usually of the greater importance; for example, in the case of an internal combustion engine cylinder it is a simple matter to work out the thickness of the walls to withstand the explosion load equal to that upon the piston head, and to allow for the shock effect of this load. If this calculation be made for an actual case, the thickness of the cylinder walls for cast iron usually works out at about $\frac{1}{8}$ inch or less. Now, it is not possible to make such a cast-iron casting of less than about $\frac{1}{4}$ inch thickness, and allowance must be made for the wear of the walls, provision for reboring after such wear, initial casting stresses, and the stress due to temperature differences occurring when working; the actual thickness adopted is therefore between $\frac{3}{16}$ inch and $\frac{1}{4}$ inch.* Numerous other examples occur in design work of dimensions being modified by practical considerations.

(1) Steady Load Stresses.

When the load is a steady or "dead" one, and invariable in amount during the life of the machine or structure, the working stress can be, relatively speaking, a high precentage of the breaking stress; it must, however, lie within the elastic limit.

The expression Factor of Safety† is usually applied to the ratio of the ultimate breaking stress to the working stress—that is:

$$\text{Factor of Safety} = \frac{\text{Ultimate Stress}}{\text{Breaking Stress}}.$$

The choice of a factor of safety in the case of a steady load will depend upon (*a*) the type of material employed; (*b*) the accuracy with which the load can be estimated or determined; (*c*) the degree or quality of workmanship in the manufacture of the member; (*d*) the possibility of subsidiary stresses, such as those due to temperature; and (*e*) chemical deterioration due to atmospheric or other exposure for long periods.

* These values refer to the machined cylinder; the rough-cast cylinder would vary from $\frac{5}{16}$ inch to $\frac{3}{8}$ inch in thickness.

† Usually denoted by the letters F.S.

The factor of safety for accurately known loads will be higher for homogeneous metals, such as the various steels, than it will be for cast metals like cast iron, brass, etc., for the latter are subjected to unknown casting stresses, due to the different rates of contraction, or cooling, of different parts. Thus, castings such as those shown in Fig. 59, will be subjected to internal stresses, owing to the thinner parts cooling more quickly than the thicker parts, and will tend to fracture in tension at the sections X-X. Uniformly thick materials are not in general subject to this effect.

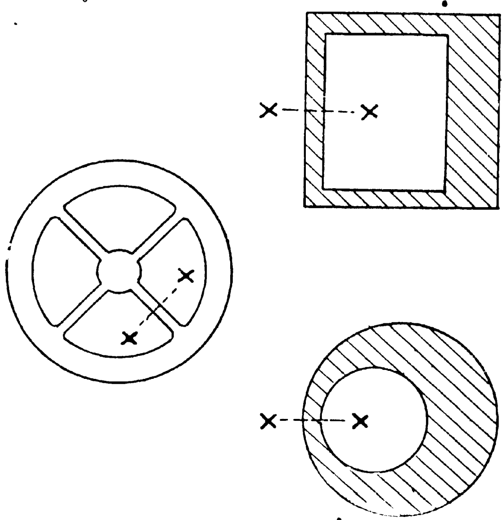


Fig. 59

For different steels the ratio of the elastic limit to the tensile strength varies, and therefore the most suitable material for dead load stresses is (other things being equal) one in which the ratio of the elastic limit to the tensile strength is the greatest. For low-carbon mild steel this ratio is about 65 per cent. For 4 per cent. nickel case-hardening steel it is 75 per cent. for the unhardened state, and 86 per cent. for the case-hardened state. For high-grade nickel-chrome steel as used for connecting-rods inlet valves, special engine gears, etc, this ratio is

60 per cent. for the unhardened state, and about 90 per cent. for the oil or air hardened state, the tensile strength being from 100 to 120 tons per square inch in this case. Lower values for the static factors of safety may be employed for these latter steels.

Again, the factor of safety for metals is always higher than that employed for timbers, for the strength of timber depends largely upon its mode of growth, the climate, soil, season of felling, nature of the seasoning process, final degree of moisture, and other uncertain factors. Moreover, the results of tensile and other tests upon certain timber specimens cannot be accurately applied to other similar timbers, unless the whole of these factors and their effects are known. Even with an efficient method of timber inspection, much higher factors of safety must be employed. For other miscellaneous materials, such as fabrics, cords, fibre, rubber, etc., the properties are usually more accurately determinable, and appropriate factors of safety can be chosen for their working conditions.

Under the circumstances considered the following are the factors of safety usually adopted for accurately known steady loads:

For steel and iron members..	from 3 to 4
For cast iron and cast metals in general ..	,, 4 ,, 5
For timber	,, 7 ,, 8
For brickwork, stone, masonry, etc. ..	,, 18 ,, 24

The above represent the minimum values under the stated conditions; in employing these results the considerations previously mentioned* should not be overlooked.

(2) Frequently Repeated Load Working Stresses.

The same general considerations apply as in the case of materials subject to steady loads, but the factors of safety will, of course, be higher. Also the F.S. for a varying load of a given range will be lower than that for a reversed load of equal range.

* *Vide* p. 132.

From the formulæ deduced from Wöhler's experimental results it will be seen that by substituting the value $n = 1\cdot5$ for ductile materials the ultimate strength for frequently repeated stresses varying from zero to a maximum occurs at one half of the static strength, whilst for stresses varying from negative to positive values the maximum stress value causing fracture, ultimately, is about one third of the static breaking strength.

Thus, if the F.S. for a steady load be 3, then for a varying load it will be 6, and for a reversed load it will be 9.

The value of the working stress can also be determined from the Launhardt-Weyrauch formula; for if the F.S. for any material under static load be denoted by r, then the value of the working unit stress f_w is given by—

$$f_w = \tfrac{2}{3}\frac{K}{r}\left(1 + \tfrac{1}{2}\frac{\text{max stress}}{\text{min. stress}}\right),$$

where K = ultimate static strength of the material

In connexion with the question of working stresses for structures subjected to both "live" and "dead" or steady loads, it is interesting to note that in the case of bridges, in which the ratio of live to dead load is large, the working stresses for good mild steel vary from $3\frac{1}{2}$ to $5\frac{1}{2}$ tons per square inch.

The corresponding values given by the above formula are—

$$\text{Working unit stress} = (2\tfrac{1}{3}\text{ to }3\tfrac{2}{3})\left[1 + \tfrac{1}{2}\frac{\text{min. load}}{\text{max. load}}\right]\ \text{tons per square inch.}$$

This formula fixes the working stress range.

(3) **Impact Stresses.**

The effects of shock and also of repetition stresses are conveniently embodied in the formula—

Equivalent dead load = maximum load + load variation.

This method reduces live loads to their equivalent dead-load value, and then treats this latter as an ordinary static load Then the F.S. is directly given by—

$$\text{F.S.} = \frac{\text{Ultimate stress}}{\text{Equiv. dead-load stress.}}$$

The following factor of safety values are recommended by Unwin, and should be regarded as being the minimum values for ordinary engineering practice. Different allowances must be made for special cases, where short or extra long endurance, liability to corrosion, bad workmanship, etc., are important considerations:

TABLE XXIX.

FACTORS OF SAFETY.

Material.	*Factor of Safety.*			
	Dead Load.	*Live or Varying Load*		*For Cases of Impact or Shock.*
		Stress of One Kind only	*Reversed Stress.*	
Cast iron ..	4	6	10	15
Wrought iron and steel	3	5	8	12
Timber	7	10	15	20
Brickwork and masonry	20	30	—	—

Factors of Safety in Aeroplane Construction.

The working stresses are generally calculated for the case of the aeroplane flying horizontally in still air, the normal "load" in this case being equal to the weight. The usual method hitherto adopted has been to choose a "factor of safety" of, say, 6 upon the normal loading stresses to allow for abnormal stresses; it will be shown that this factor of safety is inadequate and misleading.

The normal loading of a machine may be increased to many times its value under different conditions of flight. Thus, the effects of banking, diving, and flattening-out, sudden or irregular gusts, etc., all impose higher loadings upon the machine.

The following figures, based upon careful estimates of the loadings under the stated conditions, show the ratios of the

loadings under the given conditions to the normal loading upon the planes:

For banking, 1·5; for wind gusts, 4 to 5; for flattening-out after a steep dive, 5 to 7, and for looping 3 to 5, depending upon the speed.

For any combination of these conditions, the values given must be multiplied together Thus, for a sudden unfavourable wind gust whilst banking the value would be $1{\cdot}5 \times 4{\cdot}5 = 6{\cdot}75$.

The figures given for flattening-out after a steep dive represent an extreme case, which would not be realized by a careful pilot. The maximum abnormal loadings in practice could hardly exceed about *five* times the normal. Under these conditions the dimensions of the members subjected to stresses due to these loadings should be such that there is still a margin of safety in the material itself.

It is advisable to allow an initial factor of safety of about 5 to allow for the maximum abnormal loading, and a second factor of safety of between 2 and 3 to allow for material strength; the overall factor of safety will then lie between $5 \times 2 = 10$ and $5 \times 3 = 15$.

The Government at present accept aeroplanes with overall factors of safety not lower than 4, but usually between 5 and 8.

In considerations of factors of safety the nature of the loading should be taken into account. Thus, if the load is a steady or "dead" load, the factor of safety for the material may be as low as 2. For live loads, which come on frequently and vary in value, the factors of safety require to be much higher—say, from 3 to 6—in aeroplane work. As an example from engineering practice may be mentioned the three following cases for steel structures:

(*a*) Steady load, F.S. = 4.

(*b*) Load varying from zero value to a maximum, frequently, F.S. = 7.

(*c*) Load varying from a negative maximum, through zero, to a positive maximum, F.S. = 13.

The question of lightness of construction is always more or less bound up with that of the margin of safety, and the modern

tendency is to adopt larger safety factors at the expense of the weight-carrying capacity, although the increased general efficiency of the machines favours this procedure.

The greatest stresses in practice are usually associated with the wing spars. In all cases the effects of the aileron or warp loading, treated as a frequently occurring load varying from zero to a maximum, should be allowed for.

As an acceptance or check test for contract aeroplanes, it is the usual practice of the purchasers to select at random one machine in every eight or twelve, and to support this machine upside down upon trestles, and to load the lower surfaces of the wings with shot or sand in bags until they break down. If W^1 be the total breaking load upon the wings, and $2w$ the weight of the wings, and if W is the total loaded weight of the machine in flight, then the overall factor of safety is given by—

$$\text{Overall F.S.} = \frac{W^1}{W - 2w}.$$

In connexion with this method of testing the machine to destruction it is advisable to introduce, artificially, a loading equivalent to the "drift load"; and, further, to load the planes along the span and along the chord in accordance with the accepted lift distribution or pressure distribution curves for the wing aspect ratio and section.

In many cases it is usual to subject the machines to a sand-bag test, representing an abnormal loading of between four and five times the normal, before proceeding to fly the machine.

Impact Tests.

The ordinary tensile and bending tests are no true criterion of the impact-resisting qualities of a material, and in all cases in which a material is employed for parts subjected to shock or impact, tests should be made upon samples under similar conditions.

Machines* have now been devised in which suitably shaped specimens of the material are subjected to either single or to repeated blows. In some cases the specimen is given a series

* See p. 218 *et seq.*

of impacts so that tensile and compressive stresses are alternately received, as in the case of a rod which is repeatedly pulled and pushed suddenly. In another case* the specimen consists of a circular rod resting upon a pair of knife-edges, as a beam; a weight is dropped upon the centre of the beam thus formed, and between each blow the specimen is rotated about its axis through 180°, or half a turn, so that each side of the beam is alternately in tension and compression.

The simplest method of impact testing is that in which a bar is clamped at one end (as a cantilever), and in which the free end is given a blow of a known amount. The energy absorbed in bending or fracturing the bar is taken as a measure of the impact-resisting qualities of the material.

The best-known machines of this type are the Izod † and the Charpy pendulum ones, in which a pendulum of known weight is allowed to fall from a known height, and hits a cantilever type of specimen when at the lowest part of its path. The energy remaining in the pendulum is measured by the height of rebound of the pendulum. The difference between the energies before and after the blow gives the energy absorbed by the specimen.

The test may consist of fracture by a single blow or by a number of blows.

Simple Beam Impact Tests.—The simplest form of impact test is that employed for testing steel rails or cast-iron bars, by supporting these as beams at their ends and dropping a weight upon the centres of the beams. The number of blows required to produce a given deformation, or fracture is taken as a measure of the impact qualities of the materials.

In such tests the materials are tested under conditions approximating to those of their use. An American standard specification for steel axles is as follows: The axle is supported upon an anvil weighing 8 tons, resting upon springs, and the centre of the axle supports are 3 feet apart.

The radius of the supports and of the striking face of the $\frac{3}{4}$-ton hammer is 5 inches.

* See Figs. 113 and 114. † See pp. 219 and 220.

The axle is rotated through 180° after each blow, and the following are the specified maximum deflections for different-sized axles:

TABLE XXX.

American Standard Impact Test for Steel Axles.

Diameter of axle (inches)	$4\frac{1}{4}$	$4\frac{3}{8}$	$4\frac{7}{16}$	$4\frac{5}{8}$	$4\frac{3}{4}$	$5\frac{3}{8}$	$5\frac{7}{8}$
Drop in feet	24	26	$28\frac{1}{2}$	31	34	43	43
No. of blows	5	5	5	5	5	5	7
Maximum deflection in inches	$8\frac{1}{4}$	$8\frac{1}{4}$	$8\frac{1}{4}$	8	8	7	$5\frac{1}{2}$

The fatigue or shock resisting qualities of automobile and aircraft metals may be tested in the laboratory by means of the repeated impact-testing machines now obtainable for that purpose.

TABLE XXXI.

Bending Impact Test Results for Automobile Steels.

Material.	*Tensile Test Results.* *Yield Point. Tons Inches.*	*Tensile Strength. Tons Inches.*	*Elongation per Cent on 2 Inches.*	*No. of Blows to Fracture.*
Rail steel		—	—	1790
(*a*) Nickel steel (untreated)	35	46·5	27·5	2680
Case-hardening mild steel (untreated)	23	31·0	39·5	1437
(*b*) Nickel steel (untreated)	26	36·0	35·0	1740
Case-hardening nickel steel (untreated)	30	35·0	24·0	1440
(*c*) Nickel steel (heat-treated)	56	64·0	20·0	1690

The results given in Table XXXI. were obtained with the Cambridge bending impact machine described upon p. 222. The specimens were circular rods of $\frac{1}{2}$ inch diameter, and rested upon knife-edges placed at $4\frac{1}{2}$ inches apart; a tup or hammer

weighing 4·71 pounds was caused to drop repeatedly upon the centre of the specimen beam, from a height of 1·56 inches in most cases. The specimen was rotated through 180° in between each successive blow, and the blows were continued until fracture occurred; the number of blows required to fracture similar specimens is taken as a measure of the relative bending impact quality of the materials. The rate of impact-loading was about 100 per minute.

Un-notched and Notched Bar Impact Tests.—Tests upon plain un-notched bars generally agree in showing little difference between the energies required to fracture by impact or by slow statical tension; moreover, it has been shown that there is little difference in impact or slow tensional elongations at fracture.

In order to limit the plane of fracture of a bar for impact tests, and also to prevent area contraction (which does not occur in repeated or impact stress fractures), the specimen is now invariably notched. Fig. 60 shows two standard notched bar specimens for the cantilever impact test; these bars are of square section, and are intended for use in pendulum type impact machines. The upper diagram illustrates the British standard form, whilst the lower one shows the International Aircraft Standard shape of test piece. The fracture occurs with a single blow, and the residual energy in the pendulum is measured by the height of the swing after fracture.

Tension impact tests with notched specimens are sometimes made, but at present there is no reliable indication as to which is the better method; the bending impact test is usually selected, as it offers more convenience in carrying out. The residual energy may conveniently be measured by measuring rebound heights, the elongation or contraction of springs, crushing of standard tubes, and similar methods.

The impact test brings out the shock-resisting quality of the material, which is not shown by the ordinary static tests, and there is often a marked difference between the two kinds of test results; moreover, the type of crystalline fracture obtained by the impact test closely resembles that of repeated

stress specimens, the cracking occurring across the grains, with little or no elongation.

The method in question has been commercially employed for testing to destruction, in tension impact, full-sized 100-ton railway couplings, chains, and 1½-inch diameter screw threads.

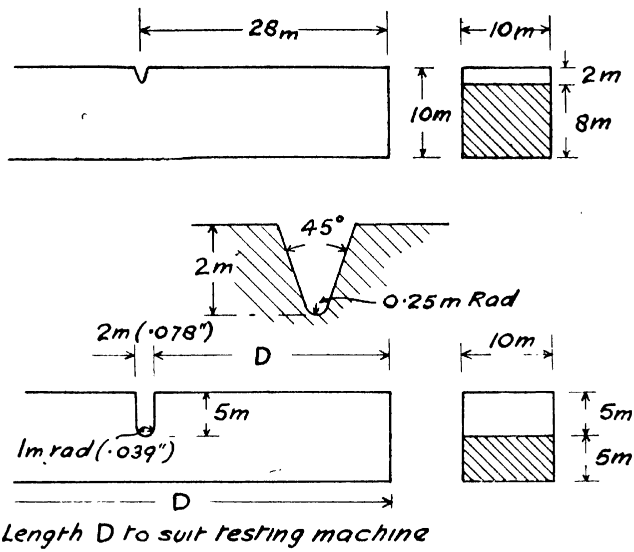


FIG. 60.—STANDARD NOTCHED BARS FOR IMPACT TEST.

Table XXXII. shows the results of the usual Izod impact tests for some typical materials.

Hardness of Metals.

The *Relative Hardness* of a metal is determined by its ability to scratch other metals; thus, one metal is harder than another when it will scratch the other. This test is, however, more accurate for brittle than for ductile materials.

The relative hardness test instituted by Moh consisted in selecting ten different minerals and arranging these in their relative orders of scratching, the softest substance having the lowest number in the scale of hardness.

TABLE XXXII.

Izod Impact Test Results.*
(Standard 10 millimetres square test piece.)

Material.	*Yield Point Tons per Square Inch*	*Ultimate Stress. Tons per Square Inch.*	*Elongation on 2 Inches per Cent.*	*Reduction of Area per Cent.*	*Average Izod Result in Foot-Pounds.*
Bright drawn mild steel bar (untreated)	36·0	37·0	24·0	59·2	12·0
Nickel-chrome steel bar †	44·0	59·3	26·0	61·9	62·1
Nickel-chrome case-hardening gear steel‡	—	50	15·0	50	45·0
Nickel-chrome case-hardening gear steel	65	85	10·0	35	20·0
Nickel-chrome oil-hardened gear steel	105	115	8·0	25	6·0
Nickel-chrome air-hardened steel	90–100	105–115	15–10	35 25	15–10
Izod Tests upon 0·2 inch bases $\frac{3}{8}$ inch wide × $\frac{5}{16}$ inch deep 0·05 inch V-notch					
Stud steel	—	31·0	30·0	—	6·9
Steel from forging	18·6–20·5	33·4 39·3	33·0–28·0	—	2·5 2·2
Steel from forging, oil tempered	20·5	39·3	28·0	—	0·7
Naval brass ..	—	26·3 30·3	19·0–28·0	—	3·7 5·5

The following were the materials and their positions in the hardness scale of Moh:

TABLE XXXIII.

Moh's Scale of Hardness.

Material.	*Order of Hardness.*	*Material.*	*Order of Hardness.*
Talc	1	Orthoclase . ..	6
Gypsum	2	Quartz	7
Calcite	3	Topaz	8
Fluorspar	4	Corundum	9
Apatite	5	Diamond	10

* Other results are given in the Tables in Chapter VI.

† Heated to 800° C., quenched in oil and tempered to 635°.

‡ Tested on the core.

Each of these materials will scratch those of lesser numerical value upon the scale, but will not be scratched by them.

It is a well-known workshop method to test the hardness of case-hardened and quenched steels by endeavouring to scratch the surface with a file.

The *Absolute Hardness* of a material is difficult to define, but the usually accepted meaning of hardness is the resistance to indentation offered by the material. The indenting body must, of course, be so hard that it will not be deformed or blunted in the process.

The *shape* of the indenting surface adopted by various experimenters has taken a variety of forms, including flat and curved knife-edges (Unwin* and Middleberg†), conical points (Calvert, Johnson, and Wade), cylinders placed across the surface to be tested (Foppl‡), truncated cones (Shore), and spherical balls (Brinell).

There are different kinds of hardness with which the engineer is associated in practice, each depending upon the special function of the part in question. For example, certain tool steels are noted for their *metal-cutting hardness*; other steels are extremely tough and possess great tensile, shear, and compressive strength, and the hardness in this case might be termed *high-stress* hardness.

Again, certain materials, such as cast iron and case-hardened alloy steels, possess hardness as a *wear-resisting* property; other instances of different types of hardnesses also occur. The hardness of a material depends upon its chemical composition, its mechanical and physical treatments. Thus, steels, aluminium, and copper alloys vary widely in hardness according to their chemical composition, indicated in Tables XXXIX. and XL.; moreover, the hardness of a material is roughly proportional to its ultimate tensile strength, which, again depends upon its composition and heat treatment.

A material may be hardened by mechanical treatment only;

* *Vide* "The Testing of Materials," p. 49, by C. Unwin.

† *Engineering*, 1856, vol. ii., p. 481.

‡ *Ann. Phys. Chem.*, 63, i., p. 103.

thus, the result of subjecting fluid steel to very high pressure, or of forging, rolling, stamping, and pressing, is to harden the material.

TABLE XXXIV.

INFLUENCE OF CARBON CONTENT IN STEEL UPON HARDNESS (SHORE SCALE).*

Percentage of Carbon.	*Hardness*	*Percentage of Carbon.*	*Hardness.*
0	19	0·25	58
0·05	24	0·30	70
0·10	35	0·35	82
0·15	43	0·40	90
0·20	51	0·45	100

Note —Each of the above steels was heated to from 1500° to 1600° F. and quenched before its hardness was measured.

Perhaps the greatest influence upon the hardness of a material is that due to heat treatment. There are two kinds of heat treatment in question—namely, one in which the temperature of the metal is changed from atmospheric to the melting-point, when the hardness progressively diminishes, and the other in which the material is heated and allowed to cool slowly or suddenly.

Thus, when a high carbon steel, as rolled during manufacture, is heated to a bright red heat—that is, to about 900° C.—and allowed to cool very slowly in ashes or sand, it becomes annealed, and its hardness is less than in the rolled state. Again, if it is heated to a bright red heat and suddenly quenched in oil or water, it becomes glass-hard and brittle; if, however, it is slowly heated to, say, 200° C. and quenched again,† it will lose part of its hardness, and will be able to cut other annealed metals, but will not be so brittle. If it is heated to 300° C.—*i.e.*, a blue temper—and quenched, it will be still less hard—namely, of about the hardness of a spring or saw blade—but more ductile, and so on, until reheating to a temperature of about 500° C. and quenching will render the material nearly as soft as in the rolled state.

Many materials, such as hardened cast steel, whilst being

* See p. 153.

† This process is known as "tempering."

extremely hard, are also brittle, whereas other materials, such as oil-hardened and tempered chrome-vanadium steel, are not only hard, but tough; each has its own special application, however.

Methods of Testing Hardness.

There are three principal methods at present in use for testing materials for hardness, which may be enumerated as follows—viz.:

1. The method in which an indenting tool of special shape is pressed with a given pressure into the surface to be tested, as in the Brinell and Unwin methods.

The depth of the indentation is taken as a measure of the hardness.

2. The "relative impression" method, which is really a modification of (1), in which an indenting tool, usually a steel ball, is placed between the surface to be tested and a surface of standard hardness. A blow of any suitable intensity is given to the standard hardness material holder with a hammer or falling weight, or the two surfaces are pressed together with any convenient means, as in a vice. The relative indentations of the surfaces indicate their relative hardnesses. This is the principle of the Brinell meter* and the Morin apparatus.

3. The rebound method, in which a diamond-tipped hammer of known weight is dropped from a given height on to the surface, and the height of the rebound is measured; this height is taken as a measure of the hardness, as in the Shore schleroscope.

Unwin's Method.†

In this method a straight square-sectioned bar is used for the indenting tool, placed diagonally to the surface, as shown in Fig. 61. The indentation depths for different pressures can be read off upon a vernier scale provided. The apparatus is designed to be placed between the compression plates of a testing machine.

* Due to F. H. Schoenfuss.

† *Vide* "Testing of Materials of Construction," p. 49. Unwin.

It has been found that there is a definite relation between the load and the depth of indentation, which may be expressed in the following manner—viz.:

$$p^n = c \cdot i,$$

where p is the pressure per inch width of the knife-edge (in tons), i the depth of indentation in inches, and c and n are constants for the material. The relative values of c are taken as the relative hardnesses.

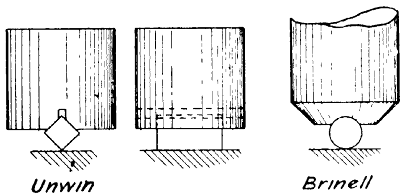


FIG. 61.

It will be seen from the following values that the value of n is very nearly constant, and may be taken as being equal to 1·20, so that the hardness relation becomes

$$c = \frac{p^{1 \cdot 2}}{i}.$$

TABLE XXXV.

VALUES OF HARDNESS CONSTANTS (UNWIN'S METHOD).

Material.	*Value of* n.	*Hardness Value* c.
Cast steel hardened in oil	—	866·0
Cast steel, annealed (mean) ..	—	523·0
Cast steel, normal	1·17	554·0
Mild steel, hardened*	—	186·7
Mild steel, annealed	—	141·9
Mild steel, normal	1·20	143·5
Brass (mean)	1·15(5)	233·5
Copper, unannealed	1·20	105·2
Copper, annealed	1·18	62·0
Aluminium alloy	1·23	103·5
Aluminium, pure (squirted) ..	1·19	41·8
Zinc, cast	1·14	40·8
Lead, cast	1·23	4·2

Note.—For calculating the values of c, n was taken as 1·2 in the above table.

* Hardened by quenching in water.

The loads per inch width of knife-edge in Unwin's test varied from about 18 tons down to a fraction of a ton in the case of lead. It will be seen that the above scale of hardness is a very wide one, so that small hardness differences are detectable.

The Brinell Hardness Method.

It has been found that the knife-edge form of indenting tool loses its sharpness after a time, so that inconsistent results varying up to 6 or 8 per cent. are possible. For this reason Brinell* employed a very hard spherical ball, which was forced into the surface of the material to be tested, with a known pressure. The area of the surface of the impression, which is proportional to the depth of the impression for a given size of ball, is taken as the hardness measure† (see Fig. 61).

The Brinell method is widely employed in aircraft and automobile engineering works, and the hardnesses of most English metals are expressed in this system.

The standard Brinell ball measures 10 millimetres (0·3937 inch) diameter, and when used upon iron and steel the impressing force is 3000 kilogrammes (6614 pounds), whilst for the non-ferrous or softer metals the force is 500 kilogrammes (1102 pounds). The diameter D of the impression formed is measured with a microscope to within 0·05 millimetre, and the area of the spherical concavity is calculated from the diameter D as follows:

$$\text{Area of curved surface of impression} = 2\pi \cdot r \cdot h,$$

where h = depth of impression, r = radius of ball.

$$A = 2\pi r\left(r - \sqrt{r^2 - \frac{D^2}{4}}\right).$$

If D and r are in millimetres, then the *Brinell Hardness Number* is expressed in the following manner:

* Invented by J. A. Brinell (in 1900), engineer of the Swedish Fagersta Iron and Steel Works.

† A description of a modern Brinell testing machine will be found upon p. 235

$$\text{Brinell number} = \frac{\text{Pressure in kilogrammes (P)}}{\text{Area of impression}} = \frac{P}{A}$$

$$= \frac{P}{2\pi r\left(r - \sqrt{r^2 - \frac{D^2}{4}}\right)} \text{ kilogrammes per square millimetre.}$$

Tables are given, similar to Table XXXVI., with Brinell instruments, in which the Brinell number is given for the various values of D, the diameter of the impression, for the standard diameter and pressures of 10 millimetres, 3000 and 500 kilogrammes respectively.

It has been found* that with higher pressures or smaller balls than the respective standards, the hardness numbers obtained by the given method are higher, the hardness obtained being directly proportional to the pressure and to the fifth root of the ball diameter; thus:

$$\text{Hardness} = \frac{P}{A}\sqrt[5]{D}.$$

Thus, if a ball of one-half of the diameter of the standard 10 millimetre size be employed, the equivalent Brinell hardness number can be found by dividing the hardness found by $\sqrt[5]{5} = 1{\cdot}38$.

Tables XXXVII. and XXXVIII. show the Brinell hardnesses of different metals.

Relation between Brinell Numeral and Tensile Strength.

It has been found that there is a definite relation between the Brinell hardness number and the elastic limit or ultimate tensile strength of a material; the latter value may be obtained from the former by multiplying by a coefficient. For hardness numbers *above* 175 the following are the relations:

Tensile strength in kilogrammes per square millimetre = Brinell No. $\times$ c,

where $c = 0{\cdot}324$ for impressions made in the direction of rolling,
and $c = 0{\cdot}344$ for impressions made transversely to the direction of rolling.

* From tests made by Brinell and Benedick.

TABLE XXXVI.—Brinell's Hardness Numbers.

(Diameter of Steel Ball = 10 millimetres.)

Diameter of Ball Impression in Millimetres.	*Hardness Number for a Load of—* 500 *kgs.*	*Hardness Number for a Load of—* 3000 *kgs.*	*Diameter of Ball Impression in Millimetres.*	*Hardness Number for a Load of—* 500 *kgs.*	*Hardness Number for a Load of—* 3000 *kgs.*
2·00	158·0	946	4·50	29·7	179·0
2·05	150·0	898	4·55	29·1	174·0
2·10	143·0	857	4·60	28·4	170·0
2·15	136·0	817	4·65	27·8	166·0
2·20	130·0	782	4·70	27·2	163·0
2·25	124·0	744	4·75	26·5	159·0
2·30	119·0	713	4·80	25·9	156·0
2·35	114·0	683	4·85	25·4	153·0
2·40	109·0	652	4·90	24·9	149·0
2·45	105·0	627	4·95	24·4	146·0
2·50	100·0	600	5·00	23·8	143·0
2·55	96·0	578	5·05	23·3	140·0
2·60	93·0	555	5·10	22·8	137·0
2·65	89·0	532	5·15	22·3	134·0
2·70	86·0	512	5·20	21·8	131·0
2·75	83·0	495	5·25	21·5	128·0
2·80	80·0	477	5·30	21·0	126·0
2·85	77·0	460	5·35	20·6	124·0
2·90	74·0	444	5·40	20·1	121·0
2·95	73·0	430	5·45	19·7	118·0
3·00	70·0	418	5·50	19·3	116·0
3·05	67·0	402	5·55	19·0	114·0
3·10	65·0	387	5·60	18·6	112·0
3·15	63·0	375	5·65	18·2	109·0
3·20	61·0	364	5·70	17·8	107·0
3·25	59·0	351	5·75	17·5	105·0
3·30	57·0	340	5·80	17·2	103·0
3·35	55·0	332	5·85	16·9	101·0
3.40	54·0	321	5·90	16·6	99·0
3·45	52·0	311	5·95	16·2	97·0
3·50	50·0	302	6·00	15·9	95·0
3·55	49·0	293	6·05	15·6	94·0
3·60	48·0	286	6·10	15·3	92·0
3·65	46·0	297	6·15	15·1	90·0
3·70	45·0	269	6·20	14·8	89·0
3·75	44·0	262	6·25	14·5	87·0
3·80	43·0	255	6·30	14·3	86·0
3·85	41·0	248	6·35	14·0	84·0
3·90	40·0	241	6·40	13·8	82·0
3·95	39·0	235	6·45	13·5	81·0
4·00	38·0	228	6·50	13·3	80·0
4·05	37·0	223	6·55	13·1	79·0
4·10	36·0	217	6·60	12·8	77·0
4·15	35·0	212	6·65	12·6	76·0
4·20	34·5	207	6·70	12·4	74·0
4·25	33·6	202	6·75	12·2	73·0
4·30	32·6	196	6·80	11·9	71·5
4·35	32·0	192	6·85	11·7	70·0
4·40	31·2	187	6·90	11·5	69·0
4·45	30·4	183	6·95	11·3	68·0

For other test loads the hardness numbers are proportional to those in the table.

TABLE XXXVII.

HARDNESSES OF E.S.C. AUTOMOBILE STEELS.*

E.S.C. No.	*Class of Steel.*	*Yield Ratio.*	*Tensile Strength. Tons Square Inch.*	*Elongation per Cent.*	*Reduction of Area per Cent.*	*Brinell† Hardness No.*
		Minimum.				
"10"	Carbon case-hardening	50	23–28	30	50	92–112
"15"	Carbon case-hardening	50	25–33	28	50	103–143
2 per cent. Ni	2 per cent. nickel case-hardening	55	25–35	30	55	103–153
5 per cent. Ni.	5 per cent. nickel case-hardening	60	25–40	30	55	103–179
"20"	0·15–0·25 carbon ..	50	26–34	28	50	105–149
"35"	0·30–0·40 carbon ..	50	30–40	25	45	121–179
3 per cent. Ni.	3 per cent. nickel ..	55	35–45	24	45	140–202
1½ per cent. Ni. Cr.	1½ per cent. nickel chrome	70	45 (min.)	15	50	179
3 per cent. Ni Cr.	3 per cent. nickel chrome	75	45 (min.)	15	50	179
A. H. Ni Cr.	Air-hardening nickel chrome in air-hardened state	75	100 (min.)	5	13	418

For materials having a hardness number *below* 175—

$c = 0{\cdot}354$ for the direction of rolling,

and $c = 0{\cdot}364$ for the direction transverse to that of rolling.

The values of the four constants in the above relation are given below for tensile strengths when expressed in pounds per square inch.

For hardness numbers above 175—

$c^1 = 460{\cdot}82$ in the rolling direction.

$c^1 = 489{\cdot}27$ across the rolling direction.

* Most of the steels referred to are in the normalized condition. For full particulars of their chemical compositions and treatment, see Chapter VI.

† The Brinell hardness number should correspond to a 3000-kilogramme pressure maintained upon a clean surface with a 10-millimetre ball for not less than 15 seconds.

TABLE XXXVIII.

BRINELL HARDNESSES OF DIFFERENT METALS AND ALLOYS.

Material.	*Brinell Number.*
Lead, cast	4–8
Babbitt metal	10–25 (cast)
Tin	15–25 (annealed or cast)
Zinc, sheet	25–40
Copper, sheet	30–60
Silver	40–70
Gold, 14–24 carat	50–140 (annealed)
Wrought iron	70–85
Bronze, phosphor, sand-cast	80–95
Mild steel	80–105 (as drawn or rolled)
Duralumin plate, medium	90–120
Brass, medium-drawn	100–150
Bronze, phosphor, chilled	100–180
Cast iron, grey, sand-cast	115–200
Brass, hard-drawn	120–170
Bronze, manganese, drawn	120–220
Nickel steel	130–160 (annealed)
Duralumin plate, hard	140–160
High-speed steel	150–260
Vanadium steel	150–300 (annealed)
Nickel-chrome steel	175–300
Tool steel, annealed	200–275
Cast iron, grey, chilled	230–400
Nickel steel, hardened	300–600
High-speed steel, hardened	450–700
Tool steel, tempered at 600° F.	550–700 (glass hard at 625)
Nickel-chrome, air-hardened	600–700

For hardness numbers below 175—

$c^1 = 503{\cdot}49$ in the rolling direction.

$c^1 = 514{\cdot}87$ across the rolling direction.

The relation between the hardness numeral and the tensile strength is given in Table XL.

The Relative Impression Method.

This method is a convenient modification of the Brinell one, in which no special apparatus is required, and which can be applied to almost any object *in situ*. Fig. 62 illustrates a typical application of the principle in the case of the Brinell

meter.* In the diagram X denotes the surface to be tested B the standard 10 millimetre Brinell ball, and S a standard bar of predetermined or known hardness. The holder H is given a blow with a hammer, or is pressed on to the surface

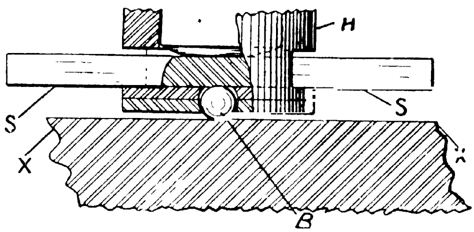


FIG. 62.—THE BRINELL METER

S, and the relative diameters of the impressions made in the surfaces S and X are proportional to their respective hardnesses.

Standard bars of square section 6 inches long are supplied, and spare bars are easily procurable with this device.

A number of different tests can be made upon each bar.

The Shore Schleroscope Method.

The hardness is determined in this method by the height of rebound of a diamond-pointed hammer dropped from a given height. The hardness number is proportional to the height of rebound of the hammer, and the scale of hardness† is so chosen that the average hardness of martensitic high carbon steel (quenched) is represented by 100; the instrument is, however, graduated to 140 from zero. The small cylindrical hammer (measuring $\frac{1}{4}$ inch diameter by [illegible] inch long, and weighing $\frac{1}{12}$ oz.) falls in a cylindrical graduated glass tube, the height of fall being 10 inches. The shape of the diamond "point" is slightly spherical and blunt, and is about 0·020 inch in diameter. The intensity of the force produced by the weight and height of fall of this hammer is equivalent to about 500,000 pounds per square inch, and since the energy

* F. H. Schoenfuss, Standard Roller Bearing Company, U.S.A.

† See Table XXXIX.

of fall is always the same, the hardnesses are simply proportional to the rebounds for different materials. Thus, for a material, such as steel, of 80 per cent. hardness 20 per cent.

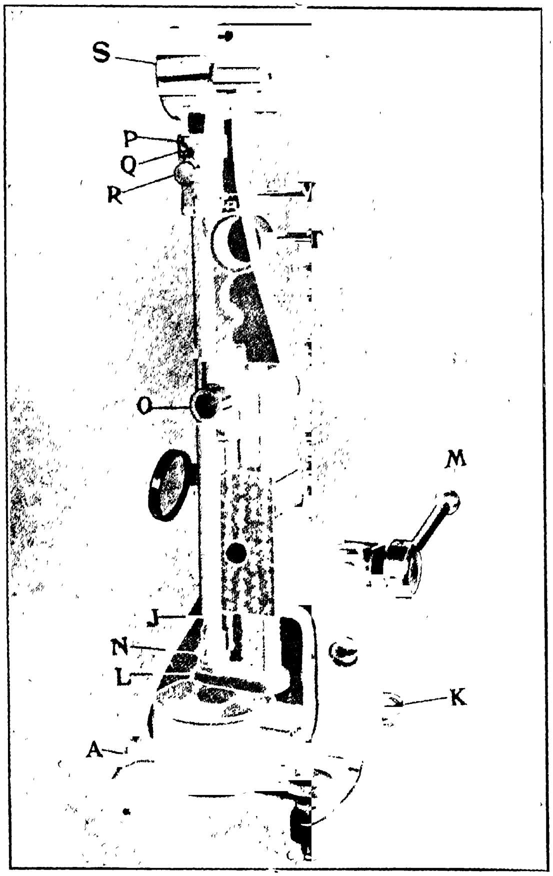


FIG. 63.—THE SHORE SCHLEROSCOPE.

of the hammer-fall energy is used up in penetrating the material, whereas in the case of lead, of hardness 5, 95 per cent. of the energy is used up in penetrating the material.

Fig. 63 illustrates the Shore schleroscope in side view, showing the automatic pneumatic release *S*, worked by the bulb *A*. The hammer is drawn or sucked up the glass tube by squeezing and then releasing the bulb *A*. To release the hammer for a test, the bulb is now again squeezed.

In using this apparatus great care should be taken in correctly levelling the vertical glass tube, otherwise incorrect results will be obtained. It is also important to provide rigid supports for the test surface, or to mount this solid with the apparatus.

In the schleroscope method it has been found that the shape and mass of the specimen influence the results. Thus a thin flat plate will be apt to deflect and to vibrate unless it is rigidly fixed to a slab underneath. In all cases the objects to be tested must be rigidly attached to a bed or base plate.

The following table gives the Shore scale values of different materials:

TABLE XXXIX.

HARDNESS VALUES OF METALS ON SHORE SCALE.

Name of Metal.	*Annealed or Cast*	*Cold Worked.*	*Chilled.*
Lead	2–4	3–7	—
Gold, 24–14 carat . ..	5–25	24–70	—
Silver	6½–14	20–37	—
Copper	6–8	14–40	—
Zinc	8–10	18–20	—
Babbitt metal	4–9	—	—
Tin	8–9	12–14	—
Bismuth	8–9	—	—
Brass	7–35	20–45	—
Platinum	10–15	17–30	—
Bronze, phosphor	12–21	25–40	—
Bronze, manganese	16–21	25–40	—
Iron, wrought, pure	16–18	25–30	—
Nickel, wrought	17–19	35–40	—
Mild steel, 0·05–0·15 carbon ..	18–25	30–40	—
Iron, grey, sand-cast	25–45	—	—
Iron, grey, chilled	—	—	50–90
Steel, tool, 1 per cent. carbon ..	30–35	40–50	90–110
Steel, tool, 1·65 per cent. carbon	38–45	—	90–110
Steel, vanadium	30–50	40–60	50–110
Steel, chrome-nickel	35–50	40–60	60–105
Steel, nickel	25–30	35–45	50–90
Steel, high-speed	30–45	40–60	70–105

TABLE XL.

COMPARISON OF BRINELL BALL AND SCHLEROSCOPE HARDNESS NUMBERS WITH COMPRESSION STRENGTH, ALSO YIELD POINT AND TENACITY OF STEEL.*

Zones of Hardness **F** *to* **A**.	*Approximate Schleroscope Hardness Number.*	*Brinell Ball Hardness Number.*	*Tensile Strength.*				*Compression. On Specimens 0·564 Inch Diameter and 0·70 Inch in Height.*		
			Yield Point.		*Maximum Stress.*		*Elastic Limit and 0·25 per Cent. Compression.*		*Compression per Cent.*
			Tons per Square Inch.	Kilogrammes per Square Millimetre	Tons per Square Inch.	Kilogrammes per Square Millimetre	Tons per Square Inch	Kilogrammes per Square Millimetre.	100 Tons per Sq. In. 160 Kilos. per Sq. Mm.
F	—	150	20	31	36	57	17	27	49·0
	—	175	26	41	41	65	19	30	40·0
	34	200	32	50	46	72	21	32	35·0
E	38	225	38	60	51	80	23	36	31·0
	42	250	44	69	56	88	26	41	27·0
	46	275	50	79	61	96	30	47	23·0
	50	300	56	88	66	104	34	54	19·0
D	54	325	61	96	71	112	38	60	15·2
	57	350	67	105	76	120	43	68	11·3
	61	375	73	115	81	128	49	77	8·0
	64	400	79	124	86	135	55	87	5·6
C	68	425	84	132	91	143	61	96	3·8
	71	450	90	142	96	151	67	105	2·4
	75	475	96	151	101	159	74	116	1·3
	78	500	102	161	106	167	81	127	0·6
B	80	525	107	169	111	175	87	137	0·23
	84	550	113	178	116	183	94	148	0·21
	86	575	—	—	122	190	101	159	0·20
	89	600	—	—	126	198	108	170	0·18

A	92	625†	Not determined	131	206	115	181	0·15
	95	650		136	214	122	192	0·14
	99	675		141	222	129	203	0·13
	101	700		—	—	136	214	0·12
A2‡	—	725	Not determined.	Not determined.		144	227	0·11
	—	750				151	238	0·09
	—	775				159	250	0·08
	—	800				166	261	0·07

The printed capital letters in the zone column refer to special sections of zones of hardness as follows

Zone.	*Brinell Ball Hardness Number.*		*Schleroscope Hardness Number*		*Yield Point. Tons per Square Inch.*		*Maximum Stress. Tons per Square Inch.*	
	From	To	From	To	From	To	From	To
F	150	200	34	34	20	32	36	46
E	200	300	50	50	32	56	46	66
D	300	400	64	64	56	79	66	86
C	400	500	78	78	79	102	86	106
B	500	600	89	89	102	Not determined.	106	126
A	600	700	—	101	Not determined.	Not determined.	126	Not determined.

* This very useful table is due to Sir Robert Hadfield (Also *vide* Presidential Address to Society of British Gas Industries, April 1918.)

† Glass-scratching hardness commences here.

‡ Owing to want of data, but little is known about this extremely high zone of "super-hardness."

Shore Hardnesses of Automobile Materials and Parts.

As the result of numerous experiments to partial and complete destruction upon actual automobile parts, the following hardness standards are recommended:*

TABLE XLI.

Part of Automobile.	*Schleroscope Hardness Standard.*
Chassis frames	(a) Plain carbon steel, 35–40 (b) Nickel-chrome steel, 40–45
Axles	Nickel-chrome (0·35 per cent. carbon), 40–45
Springs	(a) Vanadium steel, 65–80 (b) Plain carbon steel, 60–75
Crank-shafts	Nickel-chrome steel (0·35 per cent. carbon), heat-treated, 45–55
Transmission shaft	Nickel-chrome or vanadium steel, 50–55
Transmission gears	Nickel-chrome (3½ per cent. nickel), case-hardened, 80–85 [The hardness varies from 60–90, depending upon the grade of steel, and is governed by its resistance not only to shock and brittleness, but by its wearing quality.]
Pump shaft	78–80
Gudgeon pins	Case-hardened cold-drawn steel tubing, 95–100
Valve cams	85
Cam shafts	80–90
Valves	50–60
Clutch shaft gear	70–80
Valve tappets	90–100
Ball-bearing and thrust rings	85–90
Ball cones	70–80
Keys (hardened)	75–80
Screws and bolts	40–50
Steering arms	90
Steering worms	70–80

Relation between Shore and Brinell Scales.

There is no direct relation between the hardness numbers upon the two scales, since the principles involved are different, but the hardness upon the Brinell scale can be found from the Shore hardness value by multiplying by a coefficient depending upon the actual hardness of the material; thus, for the hardest steel this coefficient is about 6½, and progressively falls in value down to 2·0 for soft metals like lead.

* The Shore Instrument Company.

TABLE XLII.

COEFFICIENTS FOR MULTIPLYING SHORE VALUES TO OBTAIN BRINELL NUMBERS.

Material.	*Coefficient.*
Tool steel hardened and tempered at 600° F.	6·6
Drill rod, untreated	6·3
Brass, medium hard, drawn	5·6
Tool steel, carbon, annealed	5·5
Mild steel, hot rolled	5·25
Brass, drawn, annealed	5·0
Cast iron	4·6
Mild steel, cold rolled	4·6
Tin-lead alloy	2·0

CHAPTER III

TESTING MACHINES AND METHODS

Testing Machines.

For testing given specimens in one particular manner of loading, it is usually a fairly simple matter to design a machine for the purpose,* but when it is required to test various shapes and sizes of specimen under different types of loading, the testing machine becomes more complex in construction. It is now usual to employ testing machines which are equally adaptable for tests in tension, compression, shear, and bending; in some cases the machines are provided with the means for making torsion tests. The usual sizes of such testing machines are the 5, 10, 15, 30, 50, 100, 200, and 250 ton types, although other sizes are occasionally made; the Emery machine used at the Watertown Arsenal had a 450-ton load capacity, whilst the Olsen compression and column testing machine, which is probably the largest in the world, is of about 4500 tons capacity.

In most modern testing machines the principle is adopted of applying the load to the specimen by means of hydraulic pressure acting upon a ram coupled, through suitable means, to one end of the specimen, and to measure the applied load at the other end of the specimen by means of a sliding weight acting through a series of multiplying levers. The hydraulic ram not only applies the load, but it also takes up the stretch of the specimen, independently of the type of stress produced, and the lever system is simply kept floating as the load is applied by means of the sliding weight; the lever system may be conveniently regarded as a weighing machine.

* The machine shown in Fig. 102, p. 209, is an example.

In earlier types of machine one end of the specimen was fixed to a rigid support through suitable shackles, whilst the load was applied by an hydraulic ram, and the total load was calculated from the ram area and hydraulic pressure, making an allowance for the cup-leather friction.* This method possessed an advantage in the absence of knife-edges and levers, but some doubt always existed in the matter of the total load calculation.

In smaller sizes of testing machines the load is applied by means of a screw† and hand wheel; in other small machines, such as those employed for wire-testing, springs are used for applying the load, whilst in testing machines for yarns, belting, fabric, cement, and similar purposes, dead weight is applied through a lever system. In the latter case‡ the load is generally applied at a stipulated rate, and a hopper containing sand or lead shot is employed to run its contents at the given rate into the weight pan of the testing machine; automatic means are sometimes provided for stopping the loading immediately breakage occurs.

Another type of machine, known as the *manometric type*, arranges for one end of the specimen to act upon the diaphragm of an hydraulic pressure gauge, and the load is applied by means of a spring or screw gearing; in this method the loads can be very conveniently read off the pressure gauge, suitably engraved.

Testing machines may be divided into two types, known as the vertical and horizontal types respectively, according to whether the specimen is vertical or horizontal.

The vertical machine is the one usually preferred, as the weight of the shackle can be balanced, whereas in horizontal machines (which are chiefly used for long specimens) the weight of the shackles and other members connected to the specimen acts at right angles to the load, and it is not an easy or certain matter to counterbalance same.

* The friction $F = k \cdot D \cdot p$, where D = ram diameter in inches, p = pressure in pounds per square inch, and k = a constant varying from 0·03 to 0·05.

† The same method has also been adopted in the case of one or two very large machines, such as the Buckton and Riehlé machines.

‡ A fabric-testing machine is shown in Fig. 119.

Requirements of Testing Machines.

These may be very briefly enumerated, as follows—namely:

1. The machine should be easily adaptable for different modes of stressing and for varying sizes of specimens, within limits.

2. It should be sensitive—that is to say, it should be capable of indicating small stress differences. The sensitiveness depends upon the lever magnification, and upon the hardness and shape of the knife-edges; the radius of the knife-edge should be small and straight, and the load per lineal inch should not exceed 5 tons.

3. It should be accurate in recording loads or stresses, and its accuracy should be capable of being readily and easily checked by a simple means of calibration.

4. It must be capable of being easily manipulated by the person making the test, and should be free from vibration or jerks.

5. Convenient grips must be provided for the different specimens.

6. Autographic stress-strain recording apparatus of a reliable kind should be provided.

The Single-Lever Vertical Testing Machine.

Fig. 64 shows a photographic illustration of a 30-ton vertical type testing machine designed by Mr. W. H. Wicksteed and made by Messrs. Buckton of Leeds. In this machine the load is applied by means of a square-threaded screw, seen near the base of the machine, and the screw is operated by means of the belt-driven pulley acting through suitable gearing. The stops for the beam, *A*, are shown at *SS*, near the travelling jockey weight *w*.

The weight *w* is moved along the beam *A* by means of a square-threaded screw (not shown in photograph) and nut, operated by the handle in the centre, the shaft *T*, and a pair of chain wheels shown at the extreme left of the illustration. In this machine the specimen *E* is attached at its upper end

to the cross-head J, connected to the beam, and at its lower end to the cross-head L, which is rigidly attached to the actuating screw near the base.

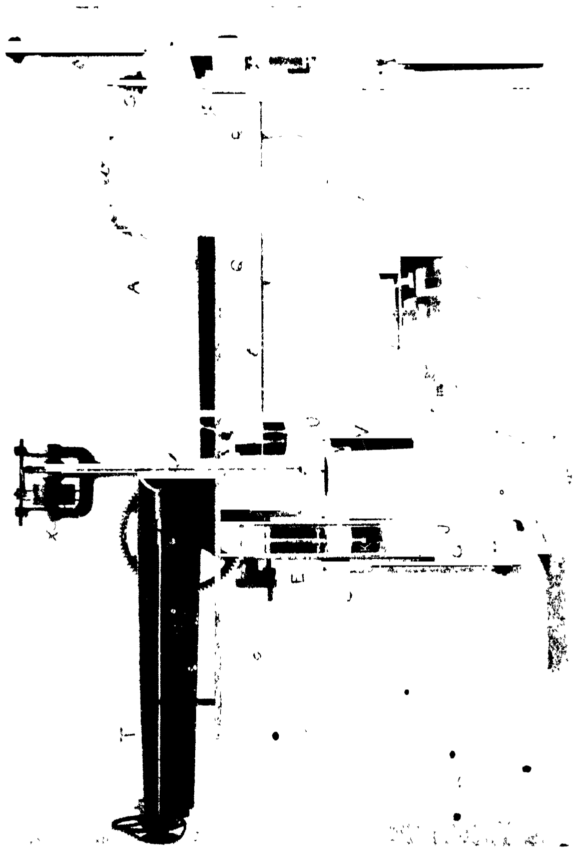


FIG. 64.—30-TON BUCKTON TESTING MACHINE

The 100-ton type of machine shown in Fig. 65 is the same in principle as the one described in the preceding paragraph, but the load is applied hydraulically by means of a valve actuated by the handle shown upon the top of the small column in the centre of the photograph. The jockey weight

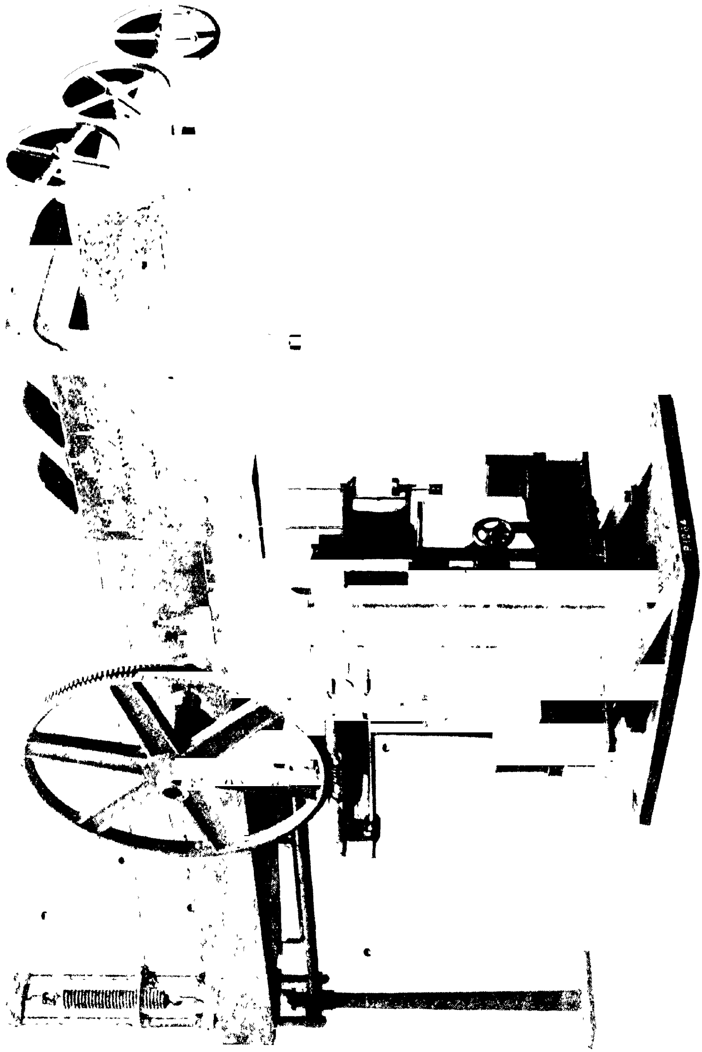


Fig. 65.—The Buckton 100-Ton Testing Machine.

is moved along the single beam by means of the horizontal handle shown, as before, and the indicator lever near the horizontal wheel, just under the beam, to the right of the vertical column, shows the operator when the load upon the specimen, applied by the ram, is balanced by the weighing beam. The beam itself is provided with an adjustable scale graduated in tons and fractions of a ton, and the 30-cwt. jockey weight has a vernier scale attached (shown in the illustration) for reading the loads off direct to one-hundredth of a ton (*i.e.*, 22·4 pounds).

This machine is capable of taking tension and compression test pieces up to 30 inches in length and beams of 72 inches span for transverse bending tests; it can also be employed for making single shear tests upon specimens with areas up to 4 square inches, and torsion tests with moments up to 100,000 pounds-inches.

The beam stops are provided with spring buffers to reduce the shock upon same at the breaking-point of specimens. It is usual to supply a weighted lever, pivoted at its centre, to force the ram up after a test, as the cup-leather and gland friction oppose this movement.

Both of the two machines previously described are provided with a single pivoted beam or lever, and possess only two knife-edge systems, so that friction is reduced to a minimum. Fig. 66 shows diagrammatically the principle of this type of testing machine.

The beam knife-edge and the shackle knife-edge are shown at B and C respectively, V being the massive cast-iron vertical column supporting the weight of the beam. The jockey weight w is movable along the scale Q, and the beam A is always kept as nearly balanced as possible between the stops S (which are usually provided with spring buffers) by moving the weight w along the beam towards the stops S as the load is applied. The manner in which the specimen E is gripped for a tension test is clearly shown; it will be observed that the hydraulic ram F acts vertically downwards, and thereby applies a load in the same direction, through the rods G and

cross-head L, to the lower end of the specimen. Trunnions or pivots are provided at each end of the specimen grips.

The force F upon the specimen, as shown in Fig. 66, is given by the relation*

$$F = \frac{w \cdot y}{x},$$

where w=weight of jockey, x is the distance shown in Fig. 66, and y the distance of the weight w from B.

The inset diagram in Fig. 66 illustrates the principle of the method of making compression tests in this type of machine.

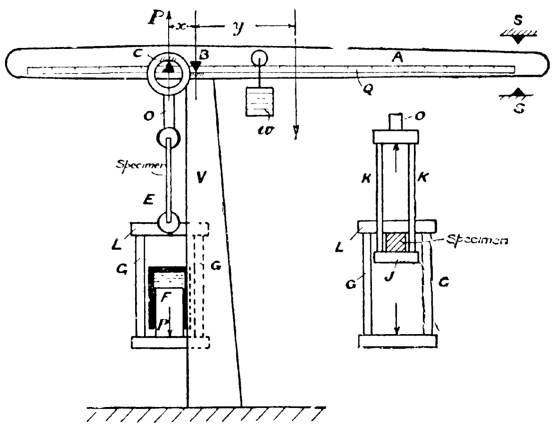


FIG. 66.

Fig. 67 illustrates the method of making transverse bending tests; instead of knife-edges for supports, semi-cylindrical rollers are often provided to take up the same direction of slope as the beam at its ends. Deflections can be measured by the same means as in the case of wooden beams.†

* It is assumed that the knife-edge friction is negligible; otherwise the relation becomes $F = \frac{w \cdot y}{x} + k \cdot w$, where k is a constant, and $k \cdot w$ represents the frictional moment about B.

† See Vol. II. of this work, Chapter VI., "The Testing of Timber."

Calibration of Vertical Testing Machines.

The two quantities which it is necessary to check in this type of machine are—(*a*) The distance between the knife-edges, and (*b*) the value of the jockey weight.

If (*b*) is determined first, then (*a*) can be easily checked. The weight of the jockey may be found by first balancing the beam, with no specimen in the beam shackles, and then by hanging a known weight m upon the beam shackle; the jockey weight has then to be moved along through a distance d to again balance the beam. If w=the jockey weight and x the knife-edge distance,

$$w=\frac{m \cdot x}{d}.$$

A better method, which is independent of the knife-edge distance, is to first balance the beam, then hang a known weight W at a distance D from the beam fulcrum B (Fig. 66). The jockey weight must then be moved along through a distance d to balance again.

$$\text{Then } w=\frac{\text{W} \cdot \text{D}}{d}.$$

Having found w, the distance x between the knife-edges may be found by the previous method, or by restoring balance by adding a known weight W to the beam at a distance D from the knife-edge B (Fig. 66).

$$\text{Then } x=\frac{\text{W} \cdot \text{D}}{m}.$$

The second method is independent of the value of the jockey weight.

Horizontal Testing Machines.

This type of machine enables tests to be more readily observed, longer specimens to be employed, and in many cases is more convenient for the larger sizes of testing machine.

The Werder type of testing machine, which is shown diagrammatically in Fig. 68, is widely used on the Continent.*

* This type of machine was employed by Bauschinger in his classical researches.

It consists of a ram connected to the fulcrum of a bell-crank lever in such a manner that the ram and lever move out at the same rate as the specimen stretches during a test. The lever is provided with a travelling jockey weight, and at its longer end is limited in movement by means of stops.

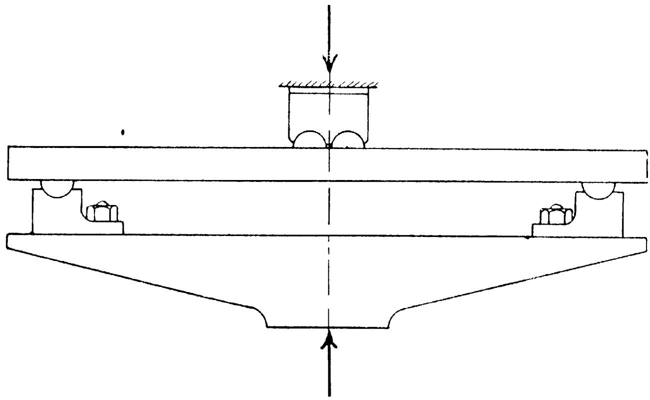


FIG. 67.—TESTING MACHINE TRANSVERSE BENDING ARRANGEMENT.

One end of the specimen is attached to a shackle fixed to the frame of the machine, whilst the other end is coupled, through a similar shackle, to the smaller arm of the bell-crank lever. In this manner it is an easy and at the same time an economical matter to provide for very long specimens

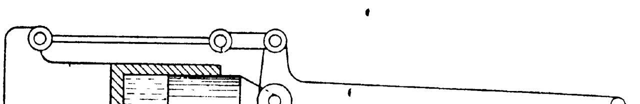


FIG. 68.—ILLUSTRATING THE PRINCIPLE OF THE WERDER TESTING MACHINE.

by moving the simple "fixed-end" supports along guides. In the 100-ton type Werder machine specimens up to 30 feet in length can be tested in tension or compression.

In the actual machine, instead of the bearings shown in the diagrammatic illustration, knife-edges are provided for the

bell-crank lever. A high ratio of leverage (500 : 1) enables small weights to be employed upon the balance arm.

Torsion and transverse tests can also be made upon this type of machine.

Compound Lever Machines—Greenwood and Batley Horizontal Type.

This machine is shown diagrammatically in Fig. 69, whilst Fig. 70 is a photographic reproduction of a 50-ton type working on the same principle.

Referring to Fig. 69, it will be seen that one end of the specimen is attached, through suitable shackles, to the hydraulic ram *G*, whilst the other end is connected to the smaller arm *F*

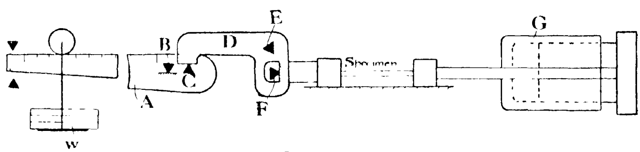


FIG. 69.

of a bell-crank lever *D*, at the knife-edge *F*, *E* being the fixed knife-edge or fulcrum. The longer arm of the lever *D* is in contact with the knife-edge *C* of a beam or weighing lever *A*, pivoted at *B*.

In this way the force, supplied by means of the ram upon the specimen, is reduced by the lever system (*D* and *A*) to a small value on the weighing arm, and is there readily balanced by means of travelling jockey weight *W*, actuated by means of a long screw, as in other types.

The leverage reduction at *W* is usually 1 to 100.

In the 50-ton type of machine shown illustrated in Fig. 70, specimens may be tested in tension, compression, bending, and shear by suitable adapters; tension specimens up to 6 feet in length may be employed. A cross-head is provided at the ram end, through which four horizontal screws pass which are geared together at their outer ends by means of spur wheels; these screws work in nuts provided in the movable cross-head. In

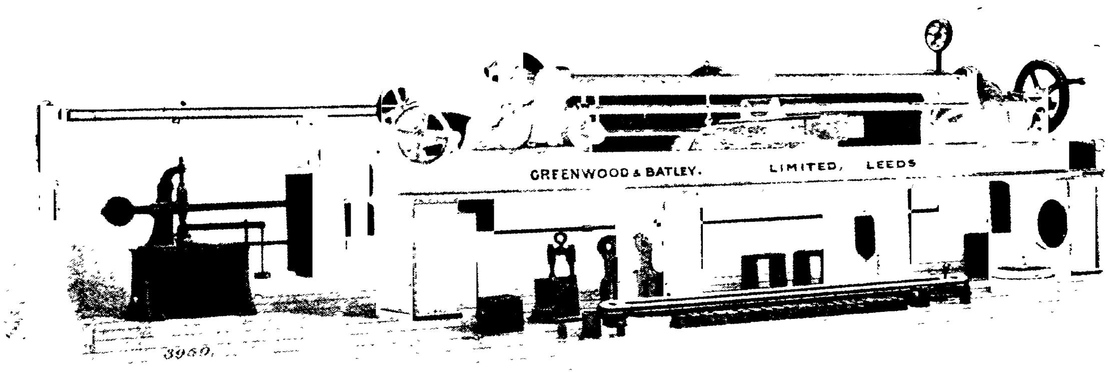


Fig. 70.—The Greenwood and Batley 50-Ton Horizontal Type Testing Machine

this manner the movable cross-head can be brought into any position along the bed to suit the length of specimen. The leverage of the weighing system is 112 to 1 in this case; the travelling weight is of the pendant type, and the weight can be varied in steps up to 1000 pounds.

Other types of testing machine are made by the same firm, in which the weighing arm is arranged over the ram and specimen, thus making a more compact arrangement, as shown in Fig. 73. In most types of horizontal machine the cross-head is arranged to move upon rollers or runners, in order to reduce friction upon the ram glands, and to take the weight from off the specimen.

The Riehlé Testing Machine.

This machine,* which is illustrated in Fig 71, is of the compound lever type, the load being applied to the specimen by means of two large vertical screws *S*. The cross-head *C* is arranged to work downwards, so that tension tests can be made in the space between *C* and *D*, and compression tests in the space between *C* and *T*. In each case the load upon the specimen is measured by the force upon the table *I*, which rests upon a pair of horizontal knife-edges seen below it in the illustration. The load is equally distributed in regard to the knife-edges of the main weighing levers, the ends of which are shown at *e* and *f*, the latter knife-edge being fixed in the second symmetrical lever. In this manner the load on the specimen is reduced to about one-sixteenth of its value at *f*; this force is further reduced through the horizontal lever *H*, which is connected at its smaller end *h*, through a rod *r*, to the weigh beam *L*. The movement of the travelling weight *W* balances the load. The ratio of the lever magnification system, when the weight is at the extreme end of the beam, is about 4500 to 1. The vertical load screws *S* are operated through the gearing shown beneath the horizontal levers, and by means of sliding dogs different speeds or rates

* Manufactured by the Riehlé Bros. Testing Machine Company, Philadelphia, U.S.A.

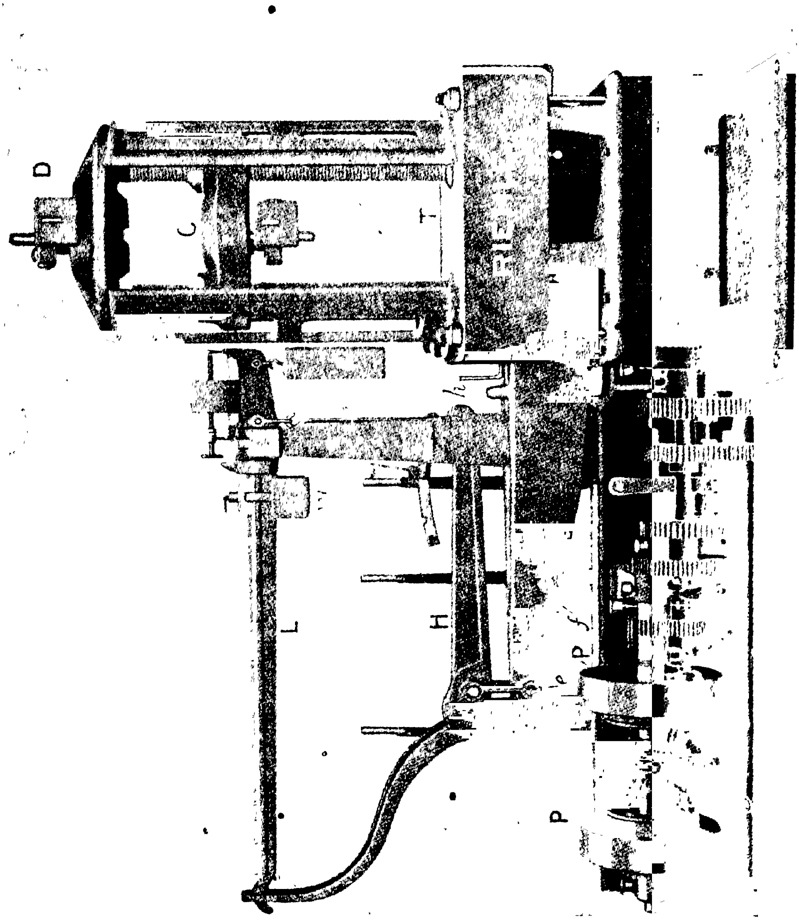


FIG. 71.—THE RIEHLÉ TESTING MACHINE

of loading can be obtained with the different gear-wheel combinations; usually an electric motor driving through a belt to one of the pulleys P is employed. In the particular machine shown a reverse gear is provided.

The Riehlé machines are made in a number of different sizes, adaptable for all kinds of tests, ranging from the 1,000,000-pound size (used for crushing tests of concrete, etc.) down to the 20,000-pound type; the machine shown in Fig. 71 is the 200,000-pound type. The principle of all the machines is the same, the mode of loading being either hydraulic or by means of either two, three, or four vertical screws geared together.

Autographic apparatus is provided for stress-strain diagrams, and an automatic controlling device can be fitted, if required, for moving the jockey weight W. Electric contacts are arranged at the end of the beam L, so that when this end rises it makes contact, and completes the circuit of an electro-magnet, which causes the weight-driving screw to be put into gear with the independent driving shaft. The weight W then moves along the beam towards the smaller end until the balance is restored and the contacts broken, when it remains in the balanced position until more load is applied.

Manometric Type Testing Machine.

In this type of testing machine one end of the specimen is attached, by suitable means, to the screw or hydraulic ram providing the necessary force, whilst the other end is connected through a cross-head and arms to a flexible diaphragm forming the cover of a chamber filled with a fluid, such as mercury. When the load is applied to the specimen, the diaphragm experiences the same force and transmits pressure to the liquid inside the chamber, which is recorded by a calibrated pressure gauge or a mercury column; the load upon the specimen is then equal to the effective* area of the diaphragm multiplied by the recorded pressure per unit area.

Fig. 72 illustrates a small machine, based upon the above

* The projected area upon a plane normal to the axis of the specimen

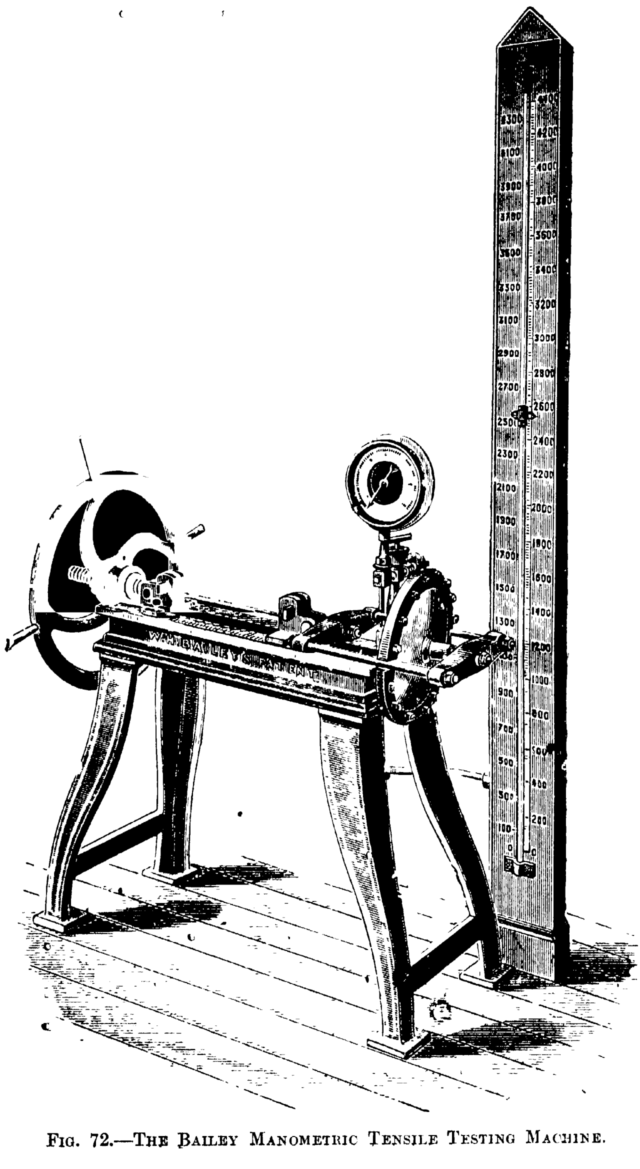


FIG. 72.—THE BAILEY MANOMETRIC TENSILE TESTING MACHINE.

principle, for testing wires, strips, rods, and cables in lengths up to about 18 inches and for loads up to 5000 pounds (in a larger type loads up to 10,000 pounds are provided for). The load is applied by means of the hand wheel shown upon the left, actuating a square-threaded screw attached to the cross-head. A quick-return motion is usually provided in this class of machine for bringing the movable cross-head back after a test.

It is essential that the diaphragm itself should offer practically no resistance, otherwise the loads will not be proportional to the pressures observed; this effect may be tested for by hanging weights over a pulley from a wire attached to the diaphragm cross-head, or by inserting a calibrated tension spring or balance in place of a specimen, and comparing the calibrated with the recorded loads.

The Thomasset testing machine is another example of the manometric principle applied on a large scale, in this machine the specimen is vertical, and the lower end is connected through shackles to an hydraulic ram. The upper end is connected to a horizontal lever at a point between the fulcrum and the smaller end, which is attached to a horizontal diaphragm consisting of a flexible metallic plate and a sheet of rubber, covering a chamber filled with mercury. The load upon the specimen is indicated by the height of mercury in the vertical gauge connected with the chamber.

The Emery testing machine, built in 1879, and installed in the Watertown Arsenal, U.S.A., also utilizes the manometric principle. This machine is capable of testing specimens up to 28 feet long and 30 inches wide in tension, and up to 30 feet long in compression, the maximum loads capable of being exerted being 360 tons and 480 tons respectively. The load is applied hydraulically, and is measured by means of a compound lever system. Between this system and the specimen is a group of four manometric diaphragms connected by small bore pipes with four other small diaphragms, the object being to reduce the loads to a much smaller value for transmission through the lever system to the weighing arm.

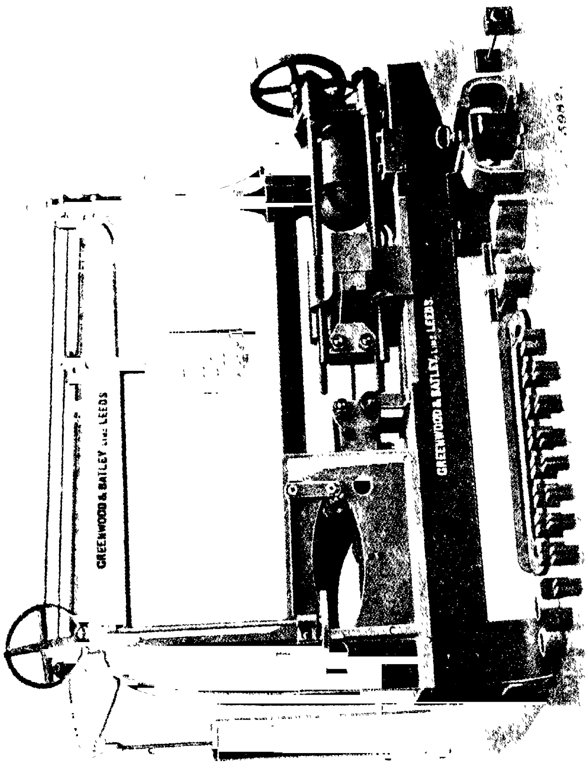


Fig. 73.—The Greenwood and Batley Compact Testing Machine.

The reduction in the diaphragm system is 20 to 1, and in the whole system 420,000 to 1. In this machine flexible steel plates or connecting strips are employed instead of knife-edges, in order to reduce the friction.

Shackles and Specimen Holders.

The design of the shackles for holding specimens in tension, compression, and shear tests, has an important influence upon the test results.

It is essential that the load shall be applied uniformly over the area of the specimen, and that for the movement of the weighing system, the line of action of the load shall always remain coincident with the axis of the specimen. The specimen* itself should be so designed that it does not fracture in or near the shackle grips.

For commercial test work it is necessary for specimens to be quickly placed in the grips, and removed after testing, without special tools or appliances.

It is usual in most testing machines to arrange for one of the cross-heads (generally upon the load-application side of the specimen) to be adjustable, for accommodating specimens of different length; this is effected by means of a screwed portion or portions of the cross-head.

The shackles between the cross-head and specimen are usually of the fork-hinged type, as shown in Fig. 74, to allow for self-alignment during loading.

Two typical methods of holding specimens are shown in Fig. 75. In the left-hand diagram the section of the specimen is enlarged where it enters the split spherical-seated collars shown, and a substantial head or shoulder is provided for taking the tensile load. The right-hand diagram shows an alternative method in which the enlarged screwed end of the specimen is held in a hardened spherical nut. It is desirable to employ rounded threads for this purpose. Fig. 77 illustrates the Riehlé self-centring specimen-holder.

* The shapes of suitable test pieces have already been considered upon p 74 *et seq*

For certain plastic materials, such as mild steel and wrought iron, wedge grips, similar to those shown in Fig. 74, are employed. The angle of the wedges is from about 1 in 6 to 1 in 8.

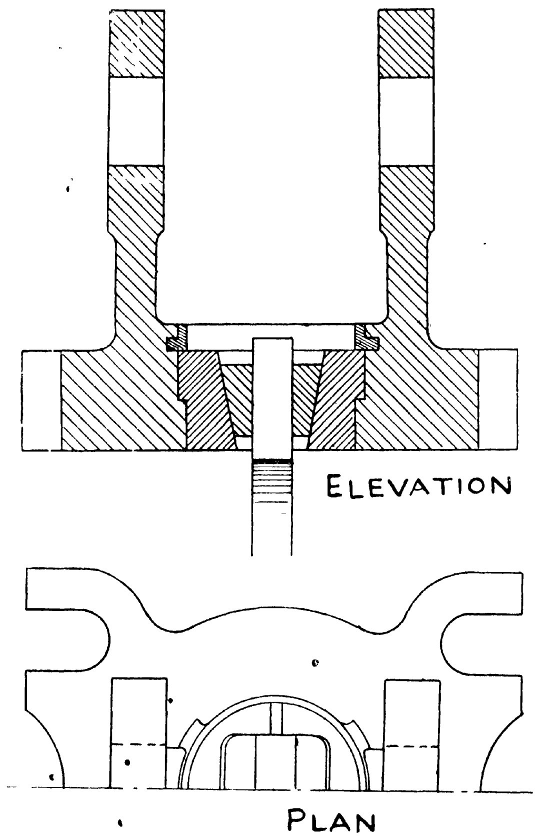


FIG. 74.—TESTING MACHINE HINGED SHACKLES WITH WEDGE GRIPS.

The surfaces of the hard-steel wedges adjacent to the specimen are roughened, similar to those of a file, whilst the other three sides are finished smooth, so that the wedges readily slide down the shackle adapters; with this method the speci-

men is gripped progressively tighter as the load increases. In the example shown in Fig. 74 it will be seen from the half-plan view that the shackle adapter for the wedges is split, and is held in position by means of the bayonet-joint ring shown. The wedge method of gripping is employed in the case of flat strips of metal.

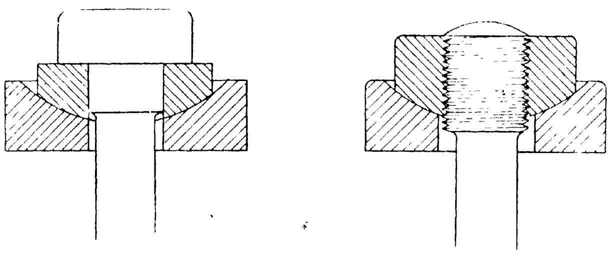
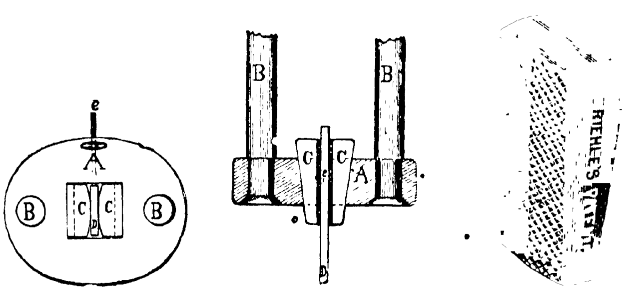


FIG. 75.—SPHERICALLY SEATED GRIPS.

Fig. 75A shows the Riehlé patent wedge grips for self-alignment of the specimen, the wedge faces upon the roughened side being rounded so as to grip the specimen more in the centre than at the outsides. The round wedge faces are shown in



1 2 4

FIG. 75A.—THE RIEHLÉ WEDGE GRIPS.

Diagrams 1 and 2 at C, D being the flat specimen, whilst Diagram 4 is a reproduction of one of the wedges showing the curved roughened face.

Fig. 79 illustrates a convenient and inexpensive form of wedge grip for testing cast iron in tension. Here the specimens

are made in the form shown in the diagram, being turned down to template; the wedge dies, as seen in plan view, are split.

For making shearing tests it is an easy matter to devise a suitable shackle upon the forked-end and eye-plate principle, with the specimen to form the connecting pin. The specimen is in double shear in this case, and in order to approximate to a pure-shearing action the specimen should be in the form of a bolt, with a clamping nut to hold the sides of the forked shackle to the eye-plate shackle, and to thus minimize bending

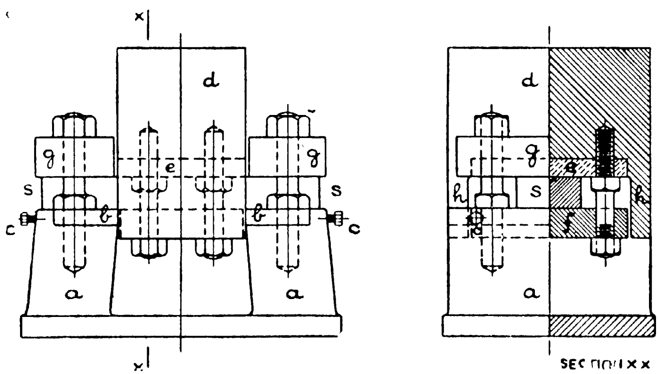


FIG. 76.—IZOD'S SHEARING SHACKLE.

action. The shearing edges of the shackle holes should be hardened; replaceable hardened bushes are found convenient in this respect.

Fig. 76 illustrates the Izod* shearing shackle for flat bar specimens. In the diagram *ss* is the specimen, which is rigidly held to the frame *a* by means of the plates *gg*, which are bolted down on to the specimen. The frame *a* forms one member of the shackle and is provided with hardened-steel shearing plates *b*, whilst the cast-iron sliding block *d*, carrying the hardened-steel shearing plate *e*, forms the other member.

A convenient form of shearing tool, suitable for making double-shear tests upon 1 inch diameter bars, is that shown in

* Proc. Inst. of Mech. Engineers, 1905.

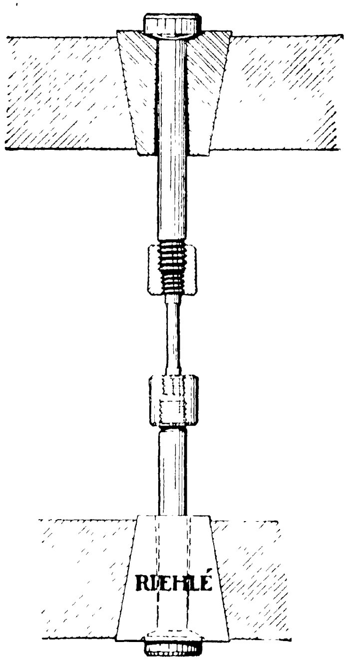


FIG. 77

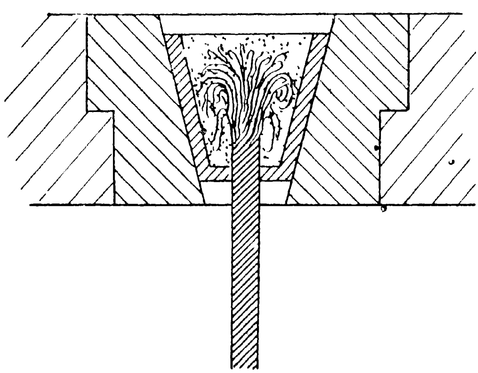


FIG. 78.

Fig. 81. The block which carries the "knives" and specimen rests on the table of the testing machine, and the movable head carrying a crushing tool forces the upper knife through the specimen. The lower cast-iron block is provided with a

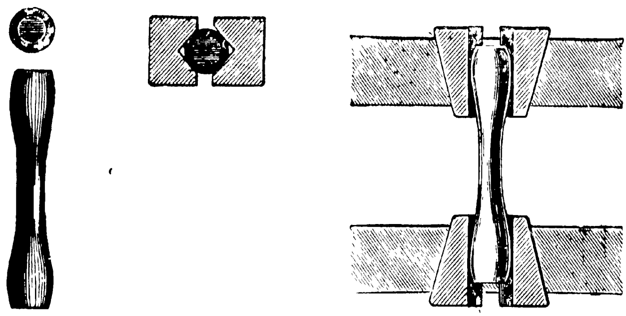


FIG. 79.—METHOD OF HOLDING CAST-IRON SPECIMENS (RIEHLÉ).

V-groove in which the specimen rests. The two lower knives are exactly 1 inch apart, and are held in the block with a wedge by which they are brought into the correct position.

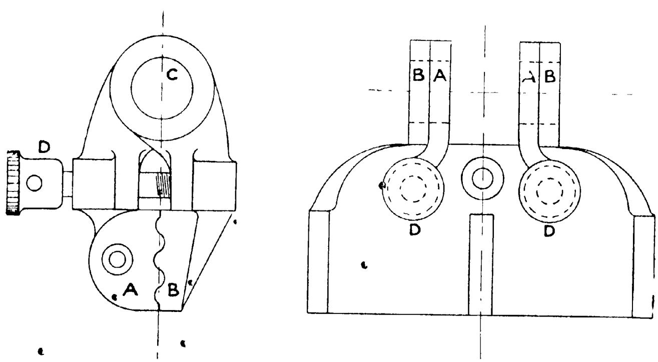


FIG. 80.—AVERY'S FABRIC TESTING MACHINE SHACKLES.

The upper knife is movable, and is guided by the block; this knife is 1 inch wide, so that it just fills the space between the lower knives when it is moved downwards.

Fig. 78 illustrates a convenient form of grip for holding steel

cable. The cable end is passed through a hollow conical thimble, and the loose wires are individually separated and bent back in various directions; the interior of the thimble is then filled with a strong kind of soft solder or alloy.* The conical thimble then tends to wedge itself in the dies of the shackles during a test.†

It is often customary to form a good splice at each end of the length of cable to be tested, and to bind with copper wire the spliced portion, finally soldering the whole splice. Ordinary pin-shackles can then be employed for holding the cable.

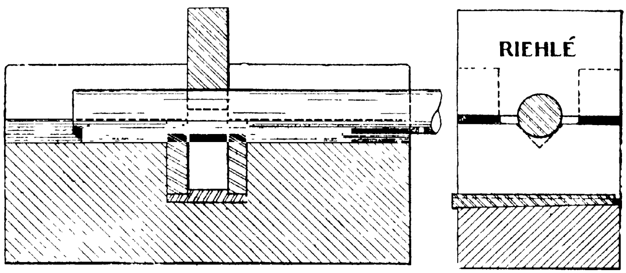


FIG. 81

Fig. 80 shows a suitable shackle for holding fabric, belting, and similar materials; this design of shackle is employed upon the Avery fabric-testing machine. The shackle consists of two hinged portions A and B, about the main link pin C, the hinging being for rapid insertion of specimens. The material is gripped between the corresponding corrugated portions of A and B by means of the bolts D, and no slipping is found to occur during a test.

Autographic Stress-Strain Recording Apparatus.

Most modern testing machines are provided with devices for automatically recording the loads and extensions of the specimens throughout a test.

The principle upon which the more common types of auto-

* A suitable alloy consists of lead 9 parts, antimony 1 part, and bismuth 1 part.

† For other suitable cable fastenings see Chapter VII.

graphic apparatus works is as follows· A cylindrical drum, upon which a sheet of paper is fastened, is caused to rotate about its axis by means of a piece of fine wire or strong cord passing around a suitable concentric pulley. The other end of the wire or cord is attached through a pulley system to the specimen, or cross-head of the testing machine, so that the rotation of the drum is proportional to the extension of the specimen. It is usual to fasten two clips to the specimen at 2, 4, 6, or 8 inches apart, as the case may be, and to arrange for the wire or cord to pass over pulleys on the clips in such a manner that the rotation of the drum is proportional to the extension occurring between the clips.

The stress component of the curve drawn upon the drum is obtained by means of a pencil carriage which is moved in a direction parallel to the axis of the drum, and which derives its motion, through a suitable reduction, from that of the rotation of the screw or the motion of the travelling cross-head (the position of which along the beam scale is proportional to the load upon the specimen).

Fig. 82 illustrates the Wicksteed-Buckton autographic recorder employed upon single-lever machines.* The rotation of the drum is obtained in a similar manner to that outlined above. The load is measured by initially setting the beam in its extreme position, by running the jockey weight along to the maximum scale reading, and by interposing a compression spring between the beam end, and its lower stop. This spring is initially compressed by the jockey weight; as the load comes on the specimen, the beam slowly rises, and the compression spring, becoming relieved of part of its load, extends. The amount of the extension is proportional to the load upon the specimen, and by coupling up the pencil carriage with the spring, the pencil will be caused to travel vertically upwards by amounts depending upon the load, and, combined with the rotational motion of the drum, a load-strain diagram will be drawn.

* This apparatus is also shown upon Fig. 64 on the extreme right-hand side.

In some forms of autographic recording apparatus it is arranged to automatically record the time of the test by means

FIG. 82.—AUTOGRAPHIC APPARATUS ON TESTING MACHINE.

of a chronograph-operated sparking set or inked pen. Elec trical methods are sometimes employed for recording small

strains within the elastic limit, for a description of which the reader is referred to Unwin's "Testing of Materials of Construction."

An early load-recording device consisted of a pencil worked from a small hydraulic cylinder's piston, the motion of the pencil being proportional to the pressure in the ram cylinder. Owing to uncertainty of ram friction, this method has not been adopted.

Extensometers.

The strains within the elastic limit are so small that special apparatus must be employed to measure same. In the case of a 2-inch specimen of mild steel the total amount of elastic strain up to the elastic limit is only about $\frac{1}{500}$ inch, or about $\frac{1}{6400}$ inch per ton per square inch load, so that a device embodying some magnification system of levers or mirrors becomes necessary.

Extensometers should be capable of measuring strains up to $\frac{1}{50000}$ inch, in order that the stress-strain relation may be obtained, and for estimating the value of moduli of elasticity.

It is also essential that the mean of the strains of the two opposite sides of the bar or specimen should be measured, as one side may, and often does, stretch more than the other, owing to slight bending or stress inequality.

The rate of loading also has an influence upon the strain measurement, and a certain time interval (usually of several seconds) should be allowed to elapse before an extensometer reading is taken.

Extensometers for commercial use should be self-contained —that is to say, when not in use should not consist of a number of loose and delicate parts; they must be easily affixed and detached, sufficiently strong in design, and reliable in use over long periods with a minimum of attention. It is usual to supply gauges with an extensometer, provided with suitable punches or indenting screws; the gauge is placed upon the specimen, and the specimen is punched or marked at the gauge

distances, say, of 2 or 8 inches, the extensometer clamping screws being placed on the marks.

Approximate Method for Finding the Yield Point.—After the elastic limit is reached, the yield point may be readily detected by placing one point of a pair of dividers in one of the gauge marks and striking a series of small arcs, backwards and forwards, across the other gauge mark; when the yield point occurs, the consecutive arcs suddenly open out by a measurable distance. After the yield point is passed, strains may be measured by means of a scale and a pair of dividers.

There are a number of extensometers upon the market, all depending upon the principle of lever or mirror magnification, and provided with microscope or vernier methods of measurement; one or two of the more important types will be here described.*

Bauschinger's Extensometer.

This extensometer consists of a pair of rollers and mirrors for measuring the strains, and enables the strains to be read off

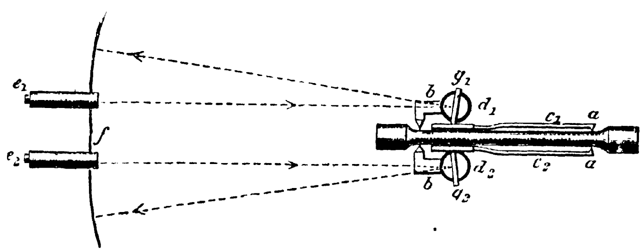


FIG. 83.—BAUSCHINGER'S EXTENSOMETER.

simultaneously upon opposite sides of the specimen. This instrument enables readings to be taken to $\frac{1}{5000}$ millimetre, or approximately to $\frac{1}{125000}$ inch.

Fig. 83 illustrates the principle of the device.

The specimen is gripped by means of separate knife-edges at a and b, which are clamped in position. The clamp at b

* For fuller information concerning other types the reader is referred to Unwin's "Testing of Materials"; Ewing's "Strength of Materials"; and E. S. Andrews's "Strength of Materials."

carries a pair of ebonite rollers, d_1 and d_2, upon well-aligned spindles, and each roller carries a mirror such as g_1 or g_2. Initially the mirrors are adjusted normally to the axis of the specimen, so that the telescopes e_1 and e_2 show reflections of the zero readings of the circular scales upon f. As the specimen stretches there is relative motion between b and a, and the rollers with their mirrors are progressively rotated, so that an observer looking through the telescopes sees the successive readings of the scales upon f.

For approximate purposes the mirrors may be replaced by long pointers moving over the same type of scale. If l be the length of the lever, arm r the radius of the roller, and x be the extension of the specimen to be measured, then

$$x = r \cdot \frac{s}{l},$$

where $s =$ the scale reading on f.

Unwin's Extensometer.

This instrument, which is shown illustrated in Fig. 84, reads the strains directly by means of the vertical scale and vernier shown.

There are two clamps, c_1 and c_2, the lower one of which carries a spirit level tube l fixed rigidly to it, but provided with zero adjustment means at s. The upper level l is free to rotate about the points of the attachment screws, one of which can be just seen behind c_1. In its normal position the upper level rests upon the top of the micrometer-wheel vertical rod m.

Initially the two levels are adjusted to parallelism; as stretching occurs, the upper level rotates or swings downwards, and the micrometer m is screwed upwards to counteract this effect, until the levels are again parallel, the amount of vertical movement being read off the scales.

Readings can be taken to within $\frac{1}{10000}$ inch with this instrument, but its use necessitates a continuous adjustment of the micrometer wheel, so that it cannot be said to be self-contained.

Ewing's Extensometer.*

This instrument, which is self-contained and very convenient and accurate to use in practice, is shown diagram-

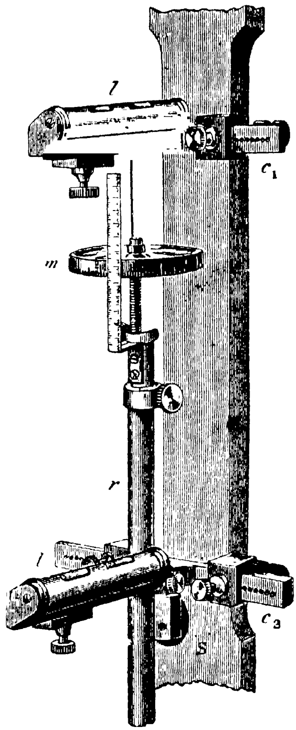


FIG. 84.—UNWIN'S EXTENSOMETER.

matically in Fig. 85 and in detail in Fig. 86. The former diagram will serve to explain the principle of the device.

There are two separate parts, clamped to the specimen at B and C respectively by means of set screws, of which C consists of a lever PCQ pivoted at C, and B is a rigid member. The rod B^1 is provided with a bearing or fulcrum at the lower

* For fuller particulars see Ewing's "Strength of Materials," pp. 77-82.

end, allowing rotation only in a plane perpendicular to that of the paper, and with a conical point at its upper end which engages in a corresponding cavity in the member C at P.

When the specimen stretches, the point B, and therefore P, moves downwards, and the point C upwards, so that the end Q and the rod R both move relatively to B through a distance

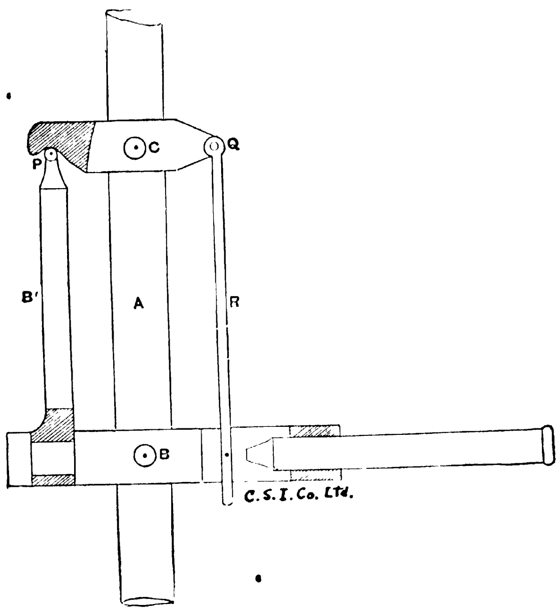


FIG. 85.—THE EWING EXTENSOMETER.

equal to twice the extension. This distance is measured by means of a measuring microscope fixed to B by observing the movement of a fixed mark upon R.

The joint between B and B^1 forms a rigid connexion between the two members, so far as angular movement in the plane of the paper is concerned; this is an essential feature in the action of the instrument, for it is only then that P serves as a fixed fulcrum in the tilting of C by extension of the specimen during a test.

Fig. 86 is an illustration of the usual form of the complete instrument. The clips B and C in this standard pattern are set at 8 inches apart.

The object sighted is one side of a wire stretched horizontally across a hole in the rod R, and illuminated by means of a small mirror behind. The distances CP and CQ are in this instance equal, with the effect that the movement of the sighted mark is double the extension of the test piece. The length of the microscope is adjusted so as to give a constant magnification.

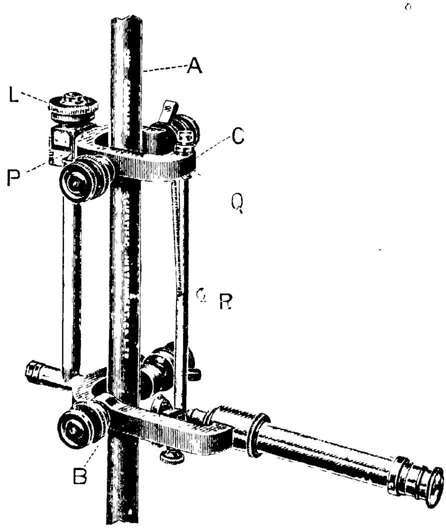


FIG. 86.—THE EWING EXTENSOMETER.

This adjustment should be tested with the extensometer mounted on the specimen, and if necessary the length of the microscope tube can be altered by drawing out or in the portion carrying the eyepiece. A complete revolution of the screw L, which has a pitch of $\frac{1}{50}$ of an inch, should cause a displacement of the mark through 50 divisions of the eyepiece scale, and when this is the case the eyepiece is at the proper distance from the objective. Readings are taken to tenths of a scale division, so that this displacement, which would also be given

by $\frac{1}{100}$ of an inch extension of the test piece, corresponds to 500 units. Each unit then means $\frac{1}{50000}$ inch in the extension of the test piece. In the instrument the whole scale comprises 1400 units, and calibration tests show that throughout the middle 1200 of them the proportionality of the scale readings with the real movements of the mark is practically perfect.

The screw L also serves to bring the sighted mark to a convenient point on the micrometer scale, and also to bring the mark back if the strain is so large as to carry it out of the field of view; thus, a single turn of the screw adds another 500 units to the range shown on the micrometer scale. In dealing with elastic strains there is no need for this, as the range of the scale is itself sufficient to include them, but it is useful when observations are being made on the behaviour of metals as the elastic limit is passed.

To facilitate the application of the extensometer to any rod a clamping bar is added by which the clips B and C are held at the right distance apart, with the axes of their set screws parallel, while they are being secured to the test piece. Such a clamping bar is especially convenient when the strain has been carried beyond the elastic limit and it is desired immediately to reset the clips to the standard distance apart after the length between them has materially changed by extension of the specimen. The clamping bar must, of course, be removed before a test begins.

A similar standard pattern of Ewing extensometer is supplied to read in metric units. In this case the length between the clips on the test piece is 20 centimetres, and the micrometer screw has a pitch of $\frac{1}{2}$ millimetre. The length of the microscope is again adjusted so that one revolution of the screw causes a displacement of 50 divisions on the eyepiece scale. Readings being taken to tenths of a division, each unit in the reading corresponds to $\frac{1}{2000}$ millimetre in the extension of the test piece.

In another pattern of Ewing extensometer, also designed for metric readings, the length between the clips on the test

piece is 10 centimetres. In this case the lever arms CP, CQ are so proportioned as to magnify the extension four times. The object sighted is a small glass slip on which are engraved horizontal lines $\frac{1}{2}$ millimetre apart. The length of the microscope is adjusted to make the space between these lines correspond to 50 divisions of the eyepiece scale, or 500 units in the readings. In this pattern of extensometer each unit consequently represents $\frac{1}{4000}$ millimetre in the extension of the test piece.

Fig. 87 shows a modified form of Ewing extensometer adapted to measure the elastic compression of short blocks having clip centres 2 inches apart. In this instrument the lever arms are arranged to magnify the movement 5 times, and the object sighted on is a small glass slip on which are engraved two fine horizontal lines $\frac{1}{50}$ inch apart. The length

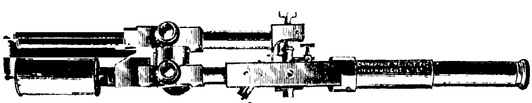


FIG. 87.

of the microscope is adjusted to make 50 divisions of the eyepiece correspond to this division of $\frac{1}{50}$ inch. Therefore, for a movement of one scale division of the eyepiece the glass slip moves through $\frac{1}{2500}$ inch and the extensometer centres move relatively $\frac{1}{12500}$ inch. In making the test, readings are taken by estimation to tenths, and a unit consequently corresponds to $\frac{1}{125000}$ inch of compression.

The compression form is also supplied for metric readings, with clip centres set 5 centimetres apart. The levers magnify 5 times, and the interval between the sighted lines on the glass slip is $\frac{1}{2}$ millimetre, which covers 50 divisions of the eyepiece scale. By estimation to tenths readings are consequently taken which correspond to $\frac{1}{5000}$ millimetre in the compression of the specimen.*

* The instruments illustrated in Figs. 85 to 87 are manufactured by the Cambridge Scientific Instrument Company, to whom the author is indebted for the loan of the diagrams.

Both of the compression forms are suitable for tension tests, on lengths of 2 inches and 5 centimetres respectively.

The Cambridge Extensometer.

This instrument, which is suitable for both scientific and commercial use, is of simple construction and gives accurate readings of the strains during a test.

The instrument is shown illustrated in Figs. 88 and 89.

It is made in two separate pieces, each of which is separately attached to the test piece *M* by hard steel conical

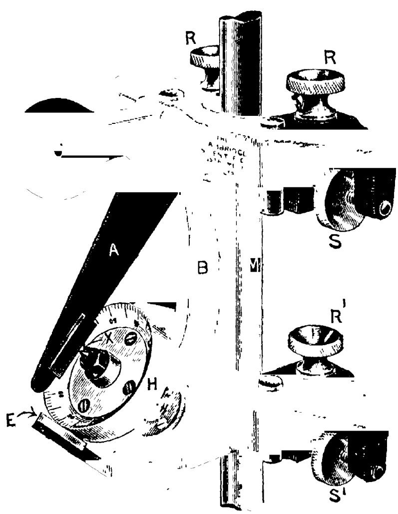


FIG. 88.—THE CAMBRIDGE EXTENSOMETER.

points *P*, *P* and P^1, P^1. The steel rods carrying these points slide in geometric slides, and after being driven gently into the centre punch marks in the test piece are clamped in position by the milled heads *R*, *R*. Both parts of the instrument should be capable of rotating quite freely about the points, but there must be no backlash.

The lower piece carries a micrometer screw fitted with a hardened steel point *X* and a divided head *H*. It also carries

a vertical arm B, at the top of which is a hardened steel knife-edge. The upper and lower pieces work together about this knife-edge. A nickel-plated flexible steel tongue A, forming a continuation of the upper piece, is carried over the micrometer point X. This tongue acts as a lever magnifying the extension of the specimen, so that the movement of the steel tongue to or away from the steel point X is five times the actual extension of the specimen.

To take a reading with the extensometer the thin steel tongue A is caused to vibrate, and the divided head then turned till

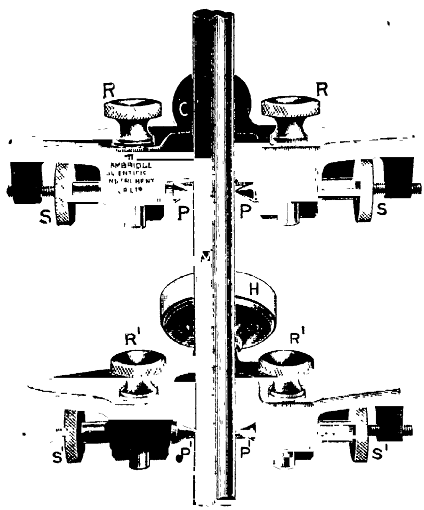


FIG. 89.—THE CAMBRIDGE EXTENSOMETER.

the point X just touches the hard steel knife-edge on the tongue as it vibrates to and fro. This has proved to be a most delicate method of setting the micrometer screw, as the noise produced and the fact that the vibrations are quickly damped out indicate to $\frac{1}{1000}$ millimetre the instant when the screw is touching the tongue. After the load is applied, a second reading is taken in a similar manner, and the difference in the readings gives directly the extension of the test piece.

If the test piece is of small diameter the spring does not vibrate in so satisfactory a manner; the cause of this is the flexibility of the test piece, the instrument itself vibrating as well as the spring. Still, very delicate readings can be taken by simply deflecting the spring with the finger and noting the contact as it passes the point. No damage can be done by advancing the micrometer screw too far forward; all that happens is that the point passes the knife-edge on one side or the other.

Dimensions.—The standard instrument is suitable for use on specimens up to 20 millimetres or $\frac{3}{4}$ inch diameter, the centre points P, P^1 being 100 millimetres apart. Instruments have also been made with the centre points 2 inches apart, and instruments for other lengths can be readily designed.

Referring to the standard instrument for 100 millimetres, the pitch of the micrometer screw is $\frac{1}{2}$ millimetre; and the head is divided into 100 parts. As the lever multiplies 5 times, each division on the head corresponds to an extension of the test piece of $\frac{1}{1000}$ millimetre, and as the tenths of divisions can be estimated by eye, readings can be taken to $\frac{1}{10000}$ millimetre, although it is not claimed that the results are trustworthy to this degree of accuracy. The effective length of the test piece being 100 millimetres, readings can be taken to $\frac{1}{1000000}$ of the length of the test piece by estimation.

This instrument has been tested by the authorities of the National Physical Laboratory, who state that "the instrument is evidently reliable to about the one-thousandth part of a millimetre under ordinary conditions of test."

It is essential, as with other types of extensometer, that the specimen should be marked off at exactly the correct centres, and that the extensometer steel-tongue centre line should pass through the centre line of the test piece. For marking off the specimen to the correct gauge length, the special marking-off tool shown illustrated in Fig. 90 is provided, and for centring the extensometer upon the test piece the centring gauge shown in Fig. 91 is particularly useful.

Torsion-Testing Machines.

Many tensile-testing machines are often provided with means for making torsion tests; one common method employed upon single-lever, vertical type machines is to provide

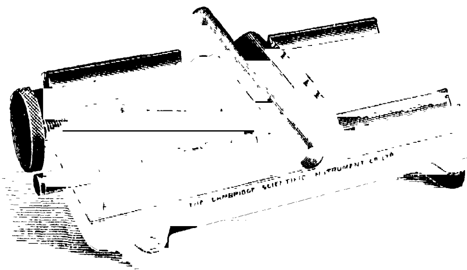


FIG. 90.

a suitable chuck having its axis coincident with the line of the knife-edges of the main fulcrum of the beam. One end of the torsion specimen, usually of square or castellated section, is

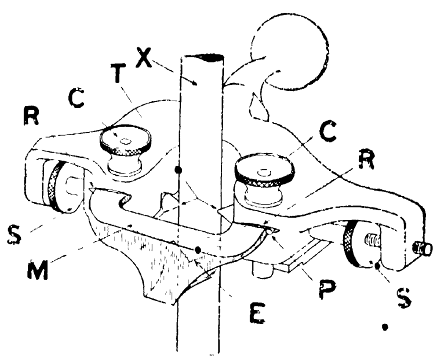


FIG. 91.

inserted in this chuck, and the other end has a similar chuck fitted in a large worm wheel, actuated by a hand wheel or gearing through a worm. As the torque is applied by means of the worm and worm wheel, the other end of the specimen

tends to rotate the weighing beam (which is initially balanced so that its C.G. coincides with the fixed fulcrum), and the torque is balanced by moving the travelling weight along the beam; the product of the weight into its distance from the axis of torsion, or fixed fulcrum, gives the torque upon the

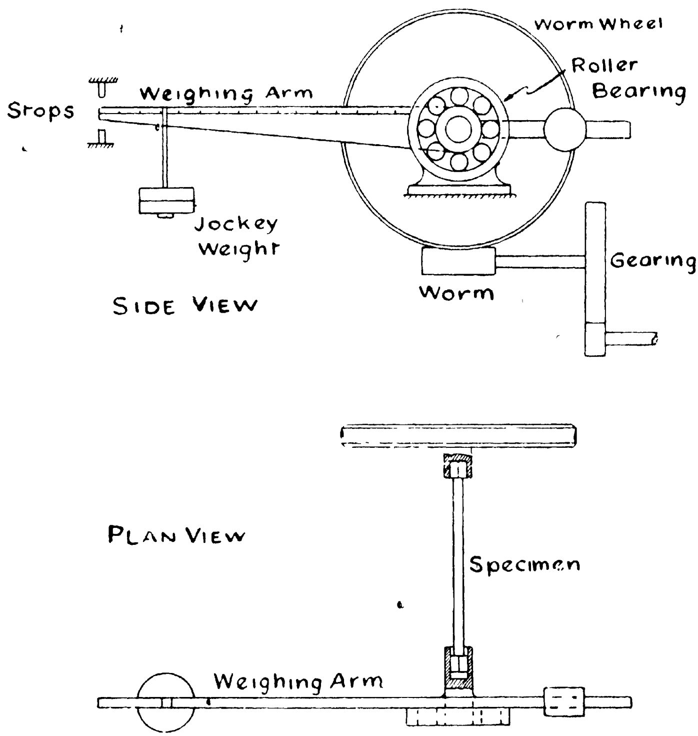


Fig. 92.—Torsion Machine Arrangement.

specimen. The worm wheel is usually provided with a dial and indicator to show the angular strains at different torques.

Fig. 92 illustrates diagrammatically the principle of the torsion attachment to a single-lever machine.

Fig. 93 shows diagrammatically two alternative methods of obtaining a pure torque, without the disadvantages of

shearing action, which is present in single-arm torsion machines.

Another method depending upon the same principle as Fig. 92 is illustrated in Fig. 94, which shows a torsion-testing machine made by Denison and Son, of Leeds, capable of applying

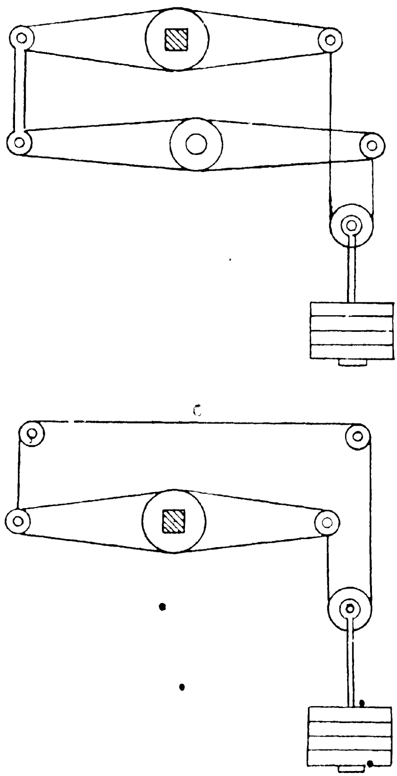


FIG. 93.

torques up to 50,000 inch-pounds. The load is applied by means of a small high-speed electric motor driving the worm and worm wheel, seen upon the right-hand side of the illustration, and this in turn works through a pair of gear wheels on to one end of the specimen. The other end of the specimen

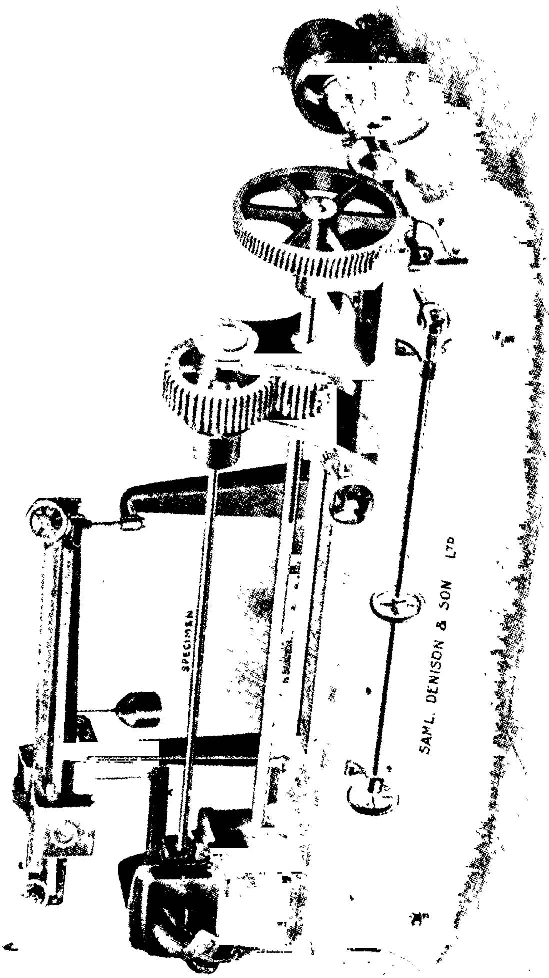


FIG. 94.—THE DENISON TORSION TESTING MACHINE.

is attached to a chuck in a lever pivoted upon knife-edges, the longer end of which pulls, by means of the tension member shown upon the left-hand side, upon one side of an initially balanced weighing arm, which records the torque upon a suitably engraved scale.

In this particular machine the travelling weight upon the weighing arm is automatically moved from its zero position along the beam as the torque is applied to the specimen, and thus always indicates, by its position, the amount of the torque at any moment.

The specimen, which is always in view, and which can be of any length up to 5 feet, is provided with squared or castellated ends, and is free to slide at one end during a test in order to accommodate the contraction in length accompanying torsional strain.

Fig. 95 illustrates another type of torsion machine, made by Messrs. Bailey and Company, and due to Professor Thurston, in which the torque is applied to the specimen by means of a hand-wheel-operated worm and worm wheel, and a pair of gear wheels, and is measured or balanced by means of a vertical pendulum upon the same axis as the specimen, which swings out of the vertical as the torque is applied, the angle of swing being a measure of the torque. Thus, if l=the distance of the C.G. of the pendulum from the axis in inches, W=its weight in pounds, and θ=its angle of deflection measured from the vertical, then the value of the torque upon the specimen is—$W \cdot l \cdot \sin \theta$ pounds-inches.

This machine is provided with an autographic recording apparatus, which consists of a cylindrical drum, upon which the paper is fixed, and which is itself concentric with and attached to the movable chuck holding one end of the specimen; the angular strains are thus directly measured. The ordinates of the curve drawn are proportional to the swing of the pendulum—that is, to the torque—the recording pencil being attached to the pendulum.

Fig. 96 illustrates the method of holding the specimen, and the templates employed to obtain the standard proportions of the specimens.

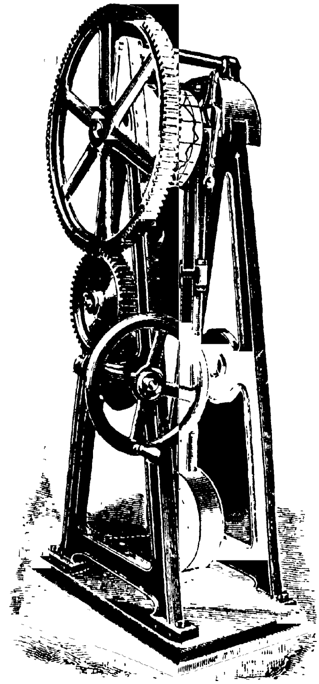


FIG. 95.—THE BAILEY-THURSTON TORSION MACHINE.

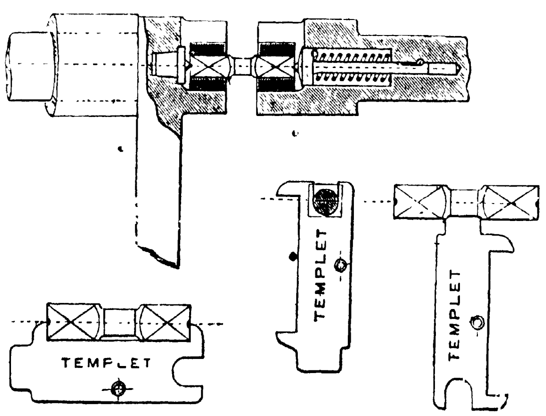


FIG. 96.

Torsion Meters.

It is usually a fairly easy matter to measure the angular strains in torsion tests, as the observed strains are relatively much greater than those occurring in tension or compression tests; thus, a circular bar of mild steel of length equal to about 10 diameters will make three or four complete revolutions at one end before it twists off.

The principle of most of the devices employed for measuring torsional strains is to fix a telescope or cathetometer upon the

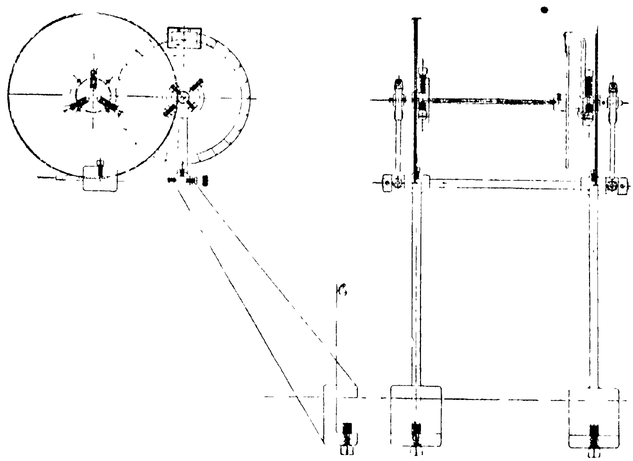


FIG. 97.—THE RIEHLÉ TORSION METER.

fixed end of the specimen, and parallel to same, at a convenient distance from the centre. The other end carries at the same radius a graduated circular scale, clamped normal to the rotating end of the specimen. Readings are made by looking through the telescope, on to the scale.

Fig. 97 illustrates the Riehlé torsion meter, which is employed for determining the elastic limit, spiral angle, and torque-strain readings to within five minutes. The device consists of two pairs of gears, each comprising a smaller and a larger gear wheel, in the ratio of 1 to 3; the smaller gear wheel of each pair is securely fixed, by means of three hardened

and pointed screws, to each end of the specimen. The larger gear wheels are carried upon a separate frame, and are provided with universal joints for alignment purposes, so that it is only necessary to take their readings with fixed verniers during a test. In this instrument the angular torsion strains are reduced in the ratio of 1 to 3. To prevent any backlash of the gears from interfering with the readings, the larger pinions are either weighted upon one side, or are provided with an automatic radial adjustment which always keeps the gears fully in mesh.

This instrument is designed to take readings over lengths varying from 2 to 10 inches, and upon diameters up to 2 inches.

Wire and Cable Testing Machines.

Wires and cables can, of course, usually be tested in ordinary tensile-testing machines, but for the smaller sizes employed in aircraft work and occasionally in light car construction, the usual tensile testing machine possesses the following disadvantages, namely:—(*a*) That the small loads cannot be accurately measured; (*b*) that the lengths of wire or cable require to be fairly short; and (*c*) that the machine is generally too massive and cumbersome to use. Where wires, small rods, or cables, require to be tested in any number, it is advisable to employ a special wire-testing machine. For aeronautical work one with a capacity up to 8000 or 10,000 pounds is convenient.

Fig. 98 illustrates an inexpensive horizontal pendulum type of wire-testing machine, made by Sir W. Bailey and Company, in which the load is applied by hand through a handle, worm, worm wheel, and screw, and is measured by the angular movement of the pendulum shown, which records the total load upon a dial. The dial, which is graduated up to 5000 pounds, is provided with a maximum pointer for marking the maximum load. An oil buffer is provided to allow the pendulum to return smoothly after a test. Specimens up to 18 inches in length can be accommodated in this machine.

Fig. 99 shows a more elaborate wire-testing machine made by Messrs. Denison and Son, with a capacity up to 10,000 pounds, and in which the load is applied at a given rate by means of an electric motor, which drives through a flat belt the worm gearing actuating the load-application screw. This machine works upon the lever principle, the loads being indicated upon a large dial provided with a maximum hand, which is pushed around by the moving hand and remains at the maximum load after fracture of the specimen. This

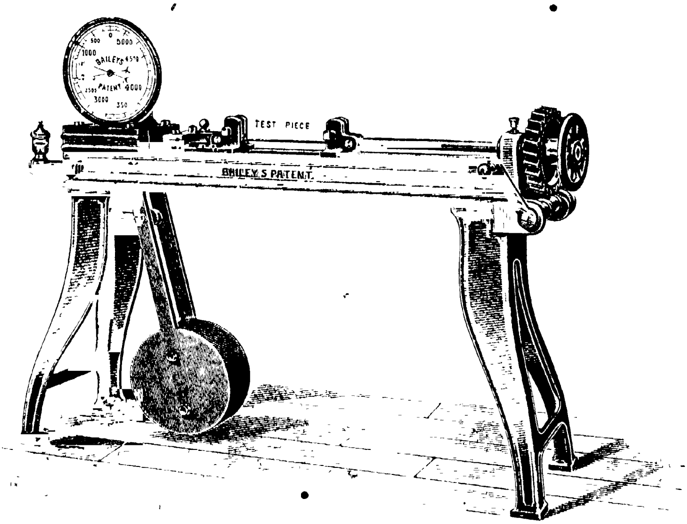


Fig. 98.—The Bailey Wire Testing Machine.

machine is also provided with autographic apparatus for drawing load-strain diagrams;* the principle of this device may be followed from the diagram, which shows the strain levers, cord, and pulleys actuated by the movement of the lower grip, which pulls a cord around the horizontal drum. The load mechanism can also be traced from the illustration. In this type of machine the wire is held in wedge grips similar

* This is very convenient for finding the elastic moduli.

in principle to those shown in Fig. 74, but with a quickly attachable arrangement for inserting the wire.

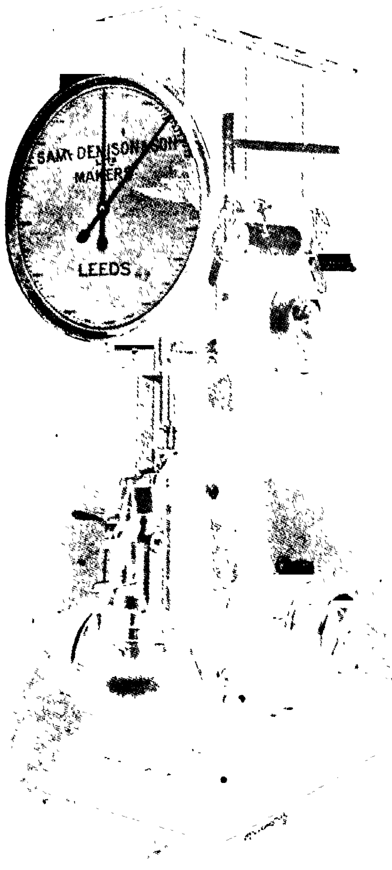


FIG. 99.—THE DENISON WIRE TESTING MACHINE (10,000 LB. TYPE).

Other types of wire-testing machine work upon the manometric principle, and the more elaborate forms are provided

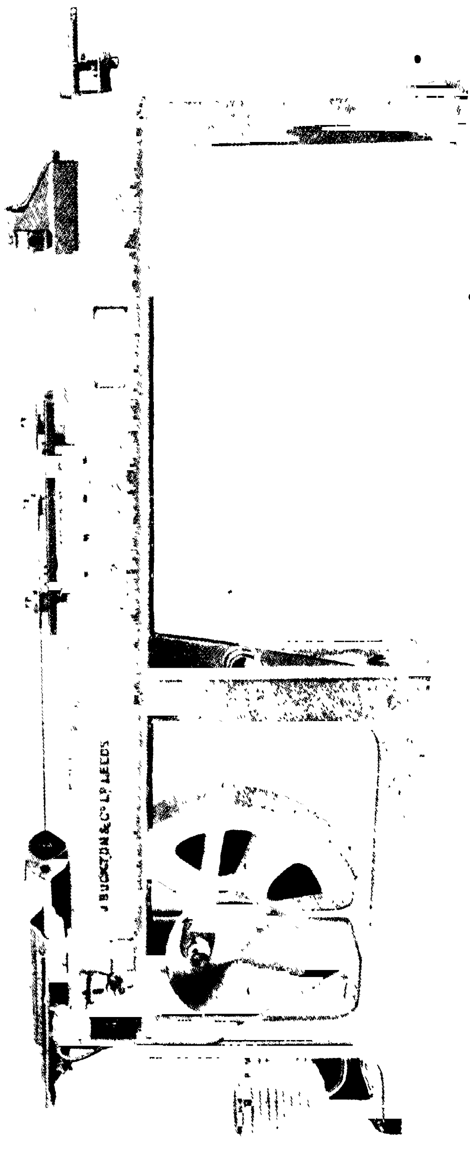


FIG. 100.—THE VAUGHAN-EPTON WIRE FATIGUE TESTING MACHINE.

with automatic devices (usually electrical in origin) for applying the load at a given rate, and for recording loads and strains.

In a large number of instances the stresses experienced by wires and cables are alternating in character, and the more common example occurring in practice is that of a wire under combined bending and tension, as in the case where pulleys are employed.

A machine, known as the Vaughan-Epton type, made by Messrs. J. Buckton and Company, has been devised for testing wire and cable in this manner, and is shown illustrated in Fig. 100. The wire or cable under test is fixed at the right-hand end in a fixed friction chuck or grip, and passes around three horizontal pulleys, the centre one of which is out of line with the other two (as shown in Fig. 101). The pulleys are carried upon a cross-head which can be driven to and fro upon the gantry of the machine by means of the crank and eccentric motion shown in the lower left-hand side. The other end of the wire or cable is attached to a chuck forming part of the ram of a horizontal cylinder, which in turn is in connexion with a small variable load accumulator by means of which a constant load of from 1 to 1000 pounds can be applied to the wire under test. A special counter is provided for recording the number of strokes of the cross-head, and means are provided for taking up the stretch of the wire, whilst keeping the constant initial load upon it. A small compensating pump is provided for supplying pressure to the accumulator. When the test has proceeded to the point when fracture of the wire occurs, the counter is thrown out of action and the driving belt is moved on to a loose pulley. It is also possible to give the wire any initial degree of torsion, if desired.

Transverse Testing Machines.

It is often necessary to make quickly a number of successive tests upon a standard size of beam, and for this purpose it is very convenient, not to add inexpensive, to employ a simple type of machine designed expressly for the purpose.

Fig. 102 shows such a form of machine, made by Messrs. W. H. Bailey and Company, for testing bars of cast iron, gun-metal, concrete, etc., in bending. This machine is de-

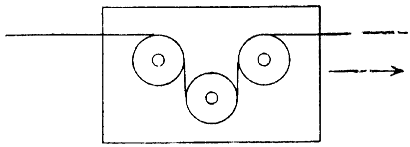


FIG. 101.

signed for bars 2 inches deep by 1 inch wide by 3 feet span, and loads up to 40 cwt. can be applied at the centre of the beams. The machine is of the single-lever type, and the sliding jockey weight is provided with a milled head for slowly moving it along the weighing arm.

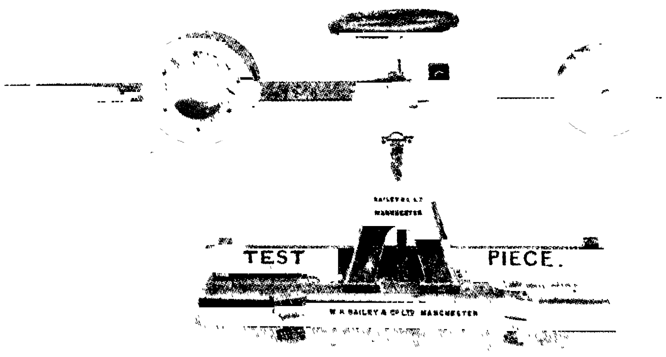


FIG. 102.—THE BAILEY TRANSVERSE TESTING MACHINE.

A more elaborate form of transverse tester, made by Messrs. Olsen, of Philadelphia, is shown in Fig. 103.

This machine is provided with an autographic apparatus for drawing large-scale load-deflection diagrams right up to the breaking-point. The weighing mechanism is of the combined lever and pendulum type, and has a capacity in the smaller type of machine of 2500 pounds, and, by employing

additional pendulum weights of 5000 pounds, in the larger type loads of 5000 pounds and 10,000 pounds are provided for.

The load is applied by means of the hand wheel and screw at a constant rate.

The sizes of test bars employed are 1 inch square by 12 inch span in the smaller machine, and 2 inches square by 24 inch span in the larger machine.

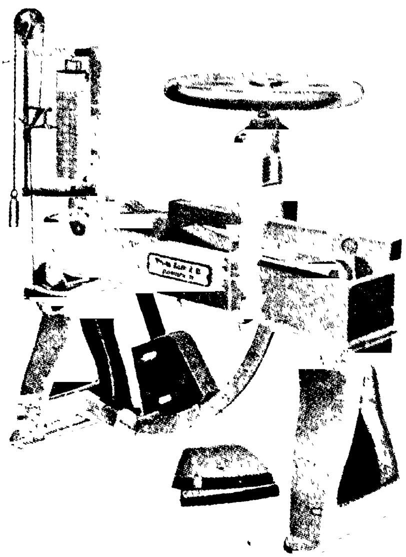


FIG. 103.—THE OLSEN TRANSVERSE AUTOGRAPHIC TESTING MACHINE.

Fatigue and Combined Stress Testing Machines.

It is becoming the practice to test specimens and members under conditions approximating to those actually occurring, for, although static tests are valuable up to a certain limit, there is not, at present, sufficient information available for predicting fatigue results from data derived from static tests.

Special machines have therefore been devised for testing machines under different systems of reversed and alternating

loadings, and for combined stresses. Machines have also been devised for repeated impact or shock tests; one or two typical examples of this class will be described later.

One of the earliest repeated-stress machines was that employed by Wöhler* for testing specimens in reversed bending action—that is, from a positive, through zero, to a negative bending moment. In this machine the specimen is held in the chuck of a lathe, as a cantilever beam, the outer end of which is loaded through a ball race with a fixed spring or dead weight. Each side of the specimen is alternately in compression and tension every revolution of the lathe spindle; the number of revolutions before fracture is recorded and the range of stress is estimated from the load and the dimensions of the specimens.

Fig. 104 shows an improved type of Wöhler machine used by the National Physical Laboratory for making tests upon welded steel joints; the principle is essentially that described above.

In this machine the number of alternations could be varied up to 2000 per minute, although, as has been already pointed out, there does not appear to be any reduction in fatigue strength due to the high rate of alternation.

The machine illustrated was provided with a revolution recorder for recording up to 10,000,000 revolutions, and was direct motor-driven. The load was applied through a Skefko spherical type ball-bearing to allow the spindle to deflect without affecting the direction of the load. A universal joint was provided between the bearing and the load, and beneath the load-weights was an oil dash pot to damp out oscillations. The hand wheel shown below the universal joint was provided with a hollow screw through which the load spindle passed, and when it was desired to take the load off, or apply the load, the screw was moved up or down to lift or release a flange upon the load rod, respectively.

The machine was automatic in action, and once started could be left running, for when the specimen broke the load

* See p. 120 *et seq.*

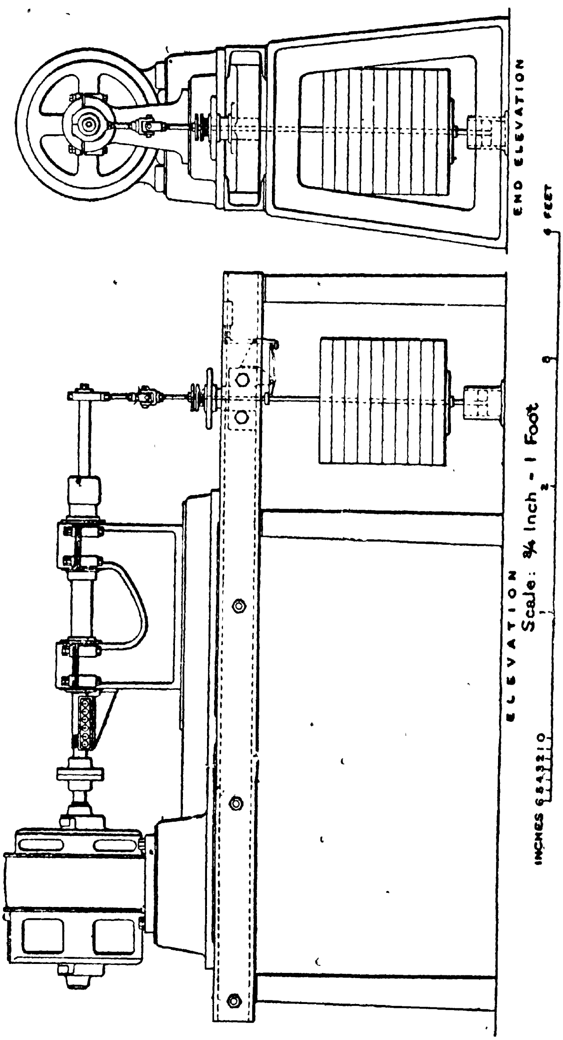


FIG. 104.—THE N.P.L. WÖHLER FATIGUE TESTING MACHINE.

and its rod dropped through a certain distance and operated a switch breaking the circuit of the electric motor. The specimens used were of 1 inch external diameter, but at the chuck end were drilled out to about $\frac{7}{8}$ inch, in order to reduce the period of the test and to enable a small, compact machine to be used.

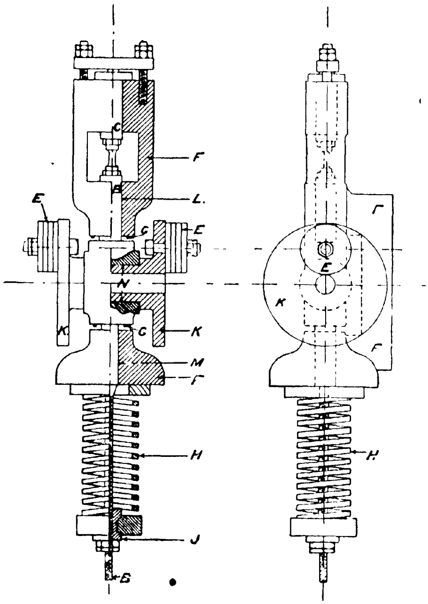


FIG. 105.—PROFESSOR SMITH'S STRESS REPETITION MACHINE.

For axle steel, with a range of reversed stress of about 36 tons per square inch, it was found that about 2,000,000 reversals were required to fracture the specimen with the above type of machine.

Another type of machine devised by Professor J. H. Smith for testing specimens in alternate tension and compression is shown illustrated in Fig. 105. In this machine a shaft N, carrying a pair of flanges K, is provided with unbalanced weights E, which as the shaft rotates introduce longitudinal

and reversed centrifugal forces upon the specimen *BC*, which is clamped at *C*; the specimen thus experiences repeatedly varying stresses. An initial tension may be applied to the specimen by means of the spring *H* and screw device *J*. The

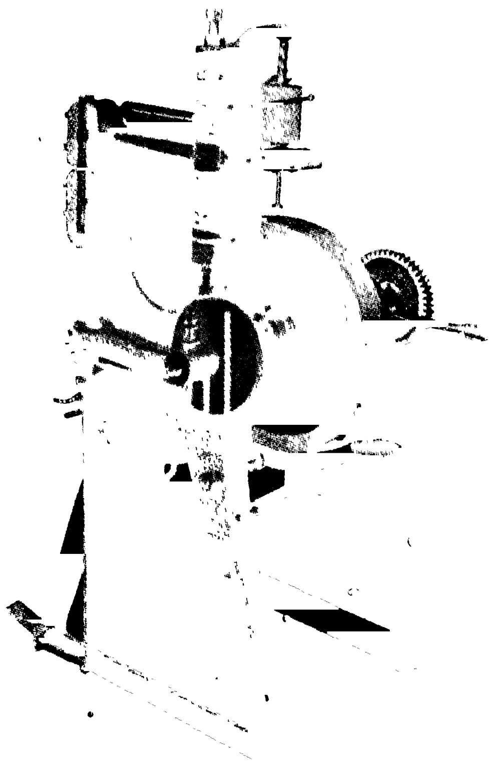


FIG. 106.—THE UPTON-LEWIS FATIGUE TESTING MACHINE.

shaft *N* is driven off another shaft in the same line with it, through a flanged plate carrying a radial slot driving one of the projections *E*; in this way the specimen receives no driving-action effect.

A machine employing this principle is used at the National Physical Laboratory for alternate tension and compression tests upon one or a number of specimens at the same time. In this type of machine the whole of the rotating parts must be balanced so that the machine and its foundations are not subjected to vibrations.

Figs. 106 and 107 illustrate another type of reversed bending machine, known as the Upton-Lewis fatigue-testing machine.* The specimen, which is of rectangular section $\frac{1}{4}$ inch × $\frac{3}{4}$ inch,

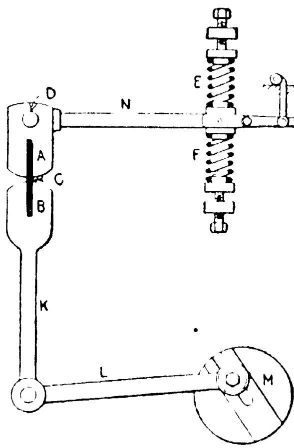


FIG. 107.

or $\frac{1}{4}$ inch × 1 inch, by 6 inches long, is clamped to the jaws *A* and *B*, thus forming the connexion between the two pieces. The jaw *A* forms part of an elbow lever *ADN*, pivoted at *D*, and provided with a pair of compression springs *E* and *F*, which can be screwed up or down so as to give any amount of stress range (one side positive and the other negative).

The reversed bending action is applied to the specimen by means of an eccentric or variable-throw crank *M*, acting through the connecting rod *L* on to the arm *KB*, thus alternately bending the specimen, first one way and then the other,

* Manufactured by Messrs. Olsen, of Philadelphia.

against each of the springs E and F in turn, until fracture occurs.

The machine is fitted with an autographic apparatus which reproduces, to scale, the compressions of the springs (which are proportional to the ranges of stress) as ordinates, and the number of alternations up to fracture, which are taken as a measure of the fatigue resistance for the given range of stress.

Fig. 108 shows a typical diagram from this type of machine; the vertical distance Y denotes the stress range, and the number of repetitions is shown by the number of peaks on one

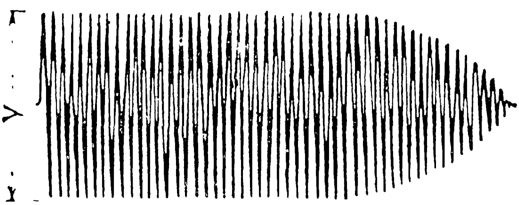


FIG. 108.—RECORD FROM UPTON-LEWIS FATIGUE MACHINE.

side. The diminishing height of the ordinates after about the fortieth alternation denotes the fatigue breakdown preceding rupture.

The Sankey Reversed Bending Machine.

This machine is a convenient one for carrying out workshop reversed bending tests by hand, and consists of an appliance for bending the specimen backwards and forwards through a fixed angle of 1·6 radians ($=91\frac{1}{2}°$) until it breaks. An autographic device records the maximum bending moment and the number of alternations, as a number of parallel strokes, somewhat similar to the records from the machine previously described. The arrangement for measuring the bending moment consists of a flat spring B (Fig. 109) clamped at one end A, and carrying at the other a grip C, between which and the bending lever E (which is about 3 feet long) the specimen D is inserted. The grip C actuates, by means of the cords

or wires L and M, the pencil H, recording the bending moment ordinates.

The test procedure is to slowly bend the specimen, by means of the lever E, until the yield point is indicated by a distinct jerk or stretching, when the drum is rotated by hand two teeth, whilst still maintaining the yield pressure; this ensures the recording of the yield bending limit. The bend is now

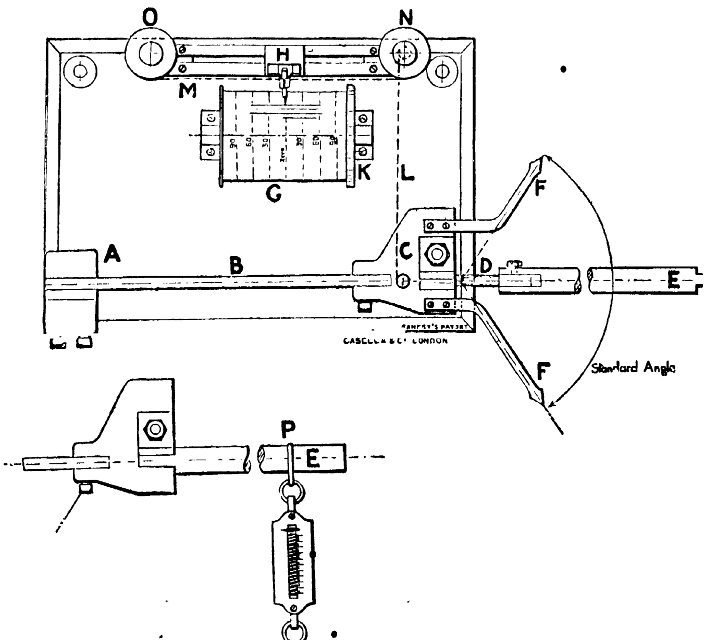


FIG. 109.—THE SANKEY HAND-BEND TESTING MACHINE.

completed to the standard angle, as indicated upon the dial FF, and the bending reversed to the other limit, and so on, until the test piece breaks, the angle of fracture being noted upon the graduated sector FF. The spring B is calibrated by applying a known bending moment to the end of the hand lever E, at P, by means of a spring balance, and adjusting the length of the spring B until the recorded moment upon the

drum corresponds with that of the spring balance. The energy required to rupture the specimen is given by—

$E = 1{\cdot}6 \times$ No. of Bends $\times$ Mean Range of Bending Moment.

The Yield Stress $= 0{\cdot}645 \times$ Initial Yield Bending Moment.

The Ultimate Stress $= 0{\cdot}645 \times$ Maximum Recorded Bending Moment.

The specimens employed have a free length of $1\frac{3}{4}$ inches.

Impact Machines.

Machines which have been devised for testing materials under conditions of impact or shock may be roughly divided into two classes—namely, (*a*) Machines for breaking the given specimen at a single blow, and provided with means for measuring the energy absorbed; and (*b*) repeated-impact machines for delivering a number of blows of known energy before fracturing the specimen.

To the former class belong the Izod, Charpy, Olsen, and N.P.L. screw-thread and railway coupling impact machines.* The latter class comprises machines such as the Cambridge drop-hammer type, the Eden-Foster, and vibratory spring testers.

The Frémont Impact Machine.

This machine is of the falling-weight type, and is often employed in automobile and engineering works for testing the shock-resisting qualities of materials.

The test piece, made to standard dimensions, is placed upon rests at the bottom of the apparatus, and a vertical column, immediately above, acts as a guide for the weight, which is allowed to drop upon the specimen.

The initial height multiplied by the weight of the hammer is a measure of the energy of the blow; the energy left in the hammer after the blow is measured by means of the deflection of a spring which receives the blow after the specimen has

* This machine has also been arranged to deliver a number of successive blows to the specimens until fracture occurs.

fractured. The difference between the two energies is that absorbed by the specimen.

The Izod Machine.

This machine,* which is shown illustrated in Fig. 110, is designed for making impact tests upon standard notched

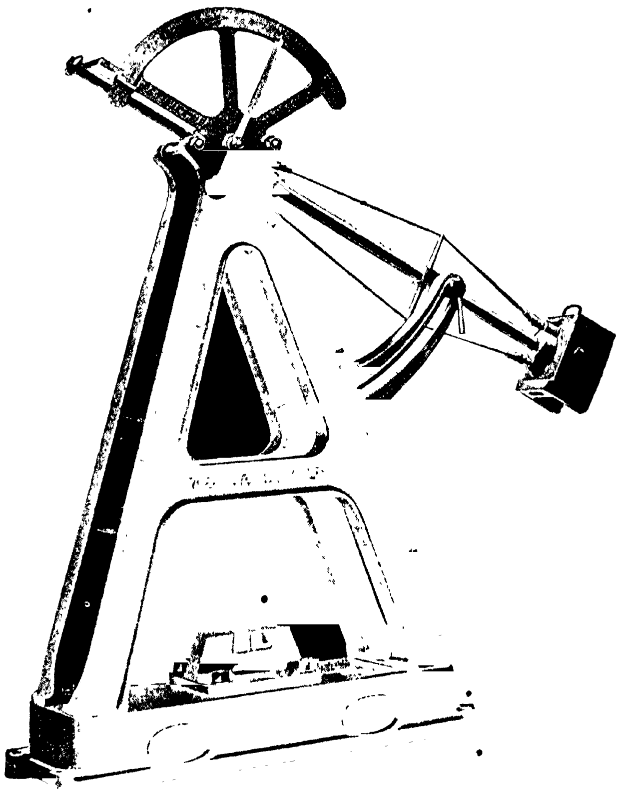


FIG. 110.—THE IZOD IMPACT MACHINE.

bar specimens.† The specimen is clamped in a vice in the position indicated in Fig. 111—that is, with the notch facing the hammer, which is of the pendulum type.

* Manufactured by Messrs. W. and T. Avery, Ltd., Birmingham

† See p. 142.

The hammer is released from an indicated angle, corresponding to a fixed height, and after striking and fracturing the specimen swings to the opposite side, to another indicated angle, from which the height after swing is determinable.

The energy absorbed by the test piece is, then, equal to the difference in heights of the C.G. of the hammer before and after impact, multiplied by its weight.

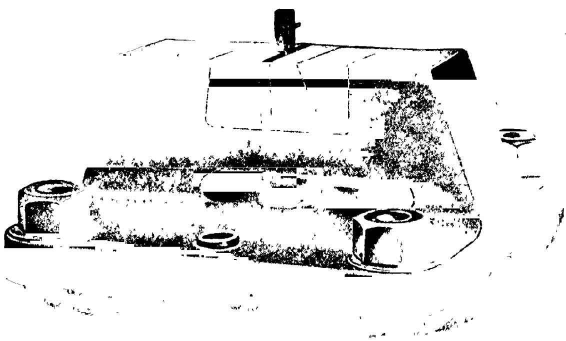


FIG. 111.—ANVIL FOR IZOD MACHINE.

The indicating scale is provided with a friction pointer, which is moved by the swinging hammer, and which indicates energies in foot-pounds, directly.

This form of machine is simple and cheap; it enables single-blow impact tests to be made very quickly, and has been found to give accurate comparative results. The maximum energy of this machine is 120 foot-pounds.

The Charpy Machine.

This machine, which is used on the Continent, is also of the pendulum type, but the hammer consists of a flat circular disc, provided with a 30° rounded striking edge; the hammer weight is 50·2 pounds, and the height of fall 51·8 inches, the total energy of the blow being about 217 foot-pounds. The notched-bar specimen is fixed at its two ends as a beam, and is struck in the centre behind the notch by the hammer striking edge.

The hammer arm swings through an angle of about 154¾° before striking the specimen, and is released by withdrawing a spring plunger, or trip; after striking, the hammer is pre-

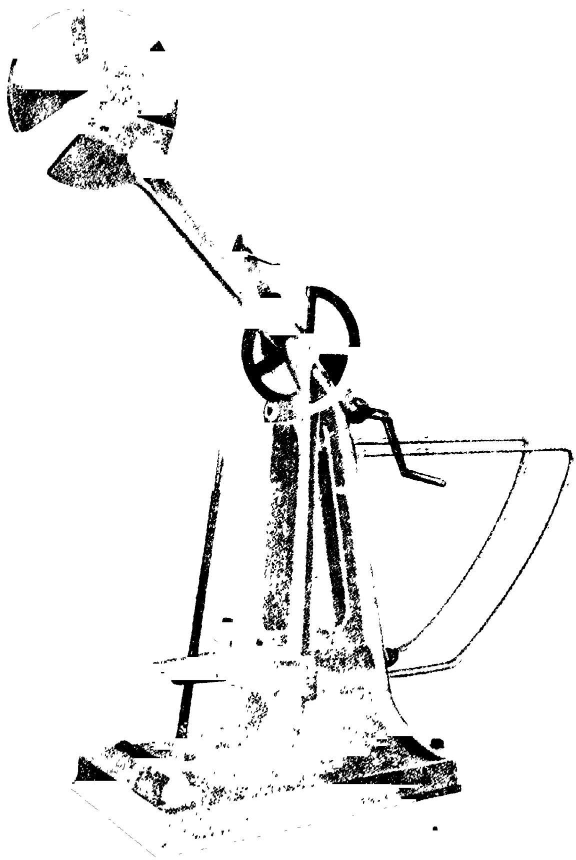


FIG. 112.—THE CHARPY IMPACT MACHINE.

vented from swinging back upon the fractured parts by means of a hand-lever-operated brake which consists of a serrated band almost coincident with the line of swing of the lowest part of the hammer. When the hand lever is pulled

towards the operator, the forward end of this band is lifted so that the hammer is wedged or caught by the band.

A hand-operated worm and worm wheel are provided for raising the hammer to its starting-point.

The results of tests made upon this machine are consistent with the Izod results.

Large Impact Machine.

A large machine of the pendulum type, designed by the author, is fitted up in the engineering section of the National Physical Laboratory, and is employed for breaking railway couplings of statical tensile breaking load up to 100 tons. The specimen is carried upon a swinging pendulum or "anvil" of nearly 5 tons weight, whilst the hammer, which weighs just under 2 tons, has a variable drop up to 12 feet. The residual energy after fracture is measured either by the final heights of swing of the pendulums or by means of a constant frictional resistance device, actuated by the anvil. The specimen can be broken either by a single blow or by a number of blows. An electrical device is employed for stopping the hammer after impact, and self-recorders for indicating the angles of swing. In all types of pendulum impact machine it is necessary to ensure that the striking face or edge is at the centre of percussion of the lever.

The Cambridge Repeated-Impact Machine.

This machine, shown illustrated in Figs. 113 and 114, was designed by Dr. Stanton, of the National Physical Laboratory, and is made by the Cambridge Scientific Instrument Company.

The specimen consists of a round notched bar *H* (Fig. 113), held in a chuck at one end and resting upon knife-edges at this end and at the other, and it is subjected to a series of blows from an almost horizontal tilt hammer *E* pivoted at *G*. Between each blow the specimen is rotated through 180°, so that it receives alternate blows upon opposite sides. The hammer is operated by means of a lifting rod *C*, supported upon a roller *D*, the locus of the end of its path being the oval-

shaped curve *E*. At this end the rod is bent at right-angles, so that on the up-stroke it engages with and lifts the hammer

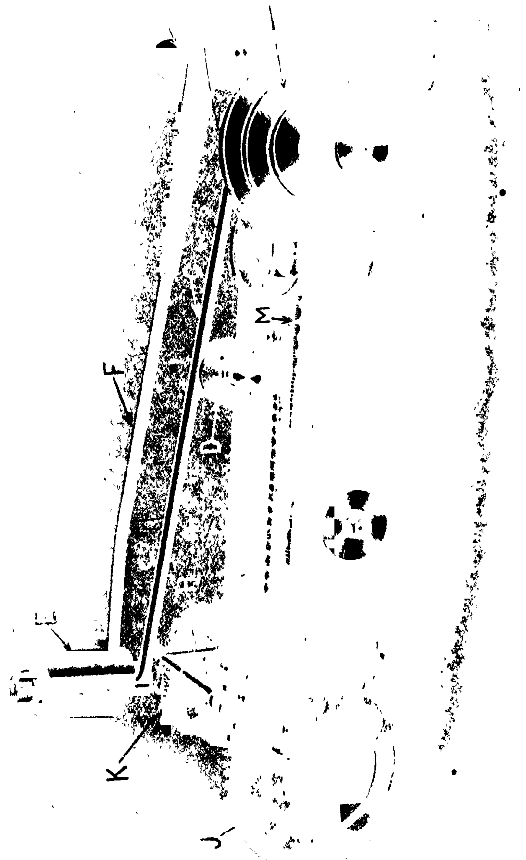


FIG. 113 —THE CAMBRIDGE REPEATED IMPACT MACHINE.

head. Having reached the top of its stroke, the lifting rod *C* slides forwards and disengages the hammer, which then falls freely upon the specimen *H*.

The number of blows delivered varies from 70 to 100 per minute, and the height of fall can be varied from 0 to 3½ inches by sliding the roller bearing *D* along a scale *M*, which is graduated to read vertical heights, directly.

The specimen is usually of about ½ inch or 12 millimetres diameter, and is supported upon knife-edges 4½ inches or 114 millimetres apart. A simple form of spring mechanism is provided for keeping the specimen stationary during the period of the blow.

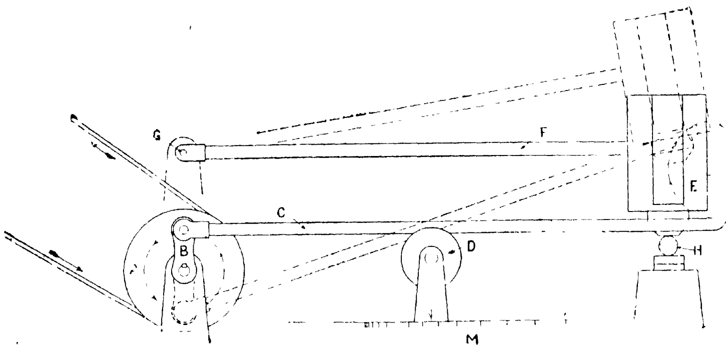


FIG. 114.—THE CAMBRIDGE REPEATED IMPACT MACHINE.

The number of blows required to fracture the specimen is taken as a comparative measure of its shock-resisting qualities. A revolution counter, to record the number of blows struck, is fixed to the base of the instrument. When fracture occurs, the specimen falls away, and the hammer head drops on to a steel stop pin, tripping an electric switch on the way, and thus cutting off the electric current to the driving motor.

The Eden-Foster Repeated-Impact Machine.

In this machine,* which is shown illustrated in Fig. 115, the notched or grooved specimen is struck by means of a freely falling vertical hammer, and, as in the case of the machine previously described, is rotated through 180° between the blows.

* Manufactured by the Foster Instrument Company, Letchworth, Herts

The illustration in Fig. 115 gives a general idea of the external appearance of the machine. The whole of the mechanism is secured to and supported by the main casting, which also acts as cover to the tank or box casting. Projecting through the side of the tank, but not seen in the illustration, is the main spindle. This may be driven by a 1-inch belt from any

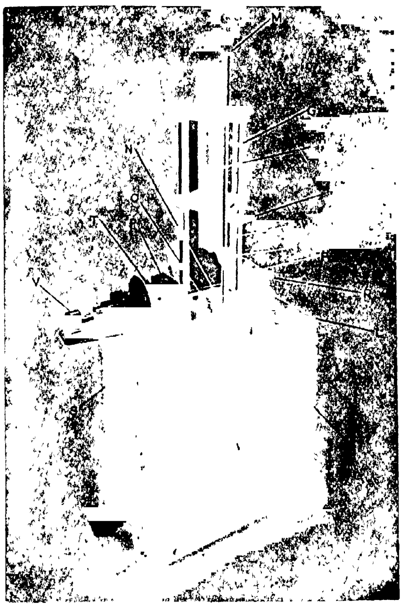


FIG. 115.—THE EDEN-FOSTER IMPACT MACHINE.

convenient countershaft, or alternatively by an electric motor, with suitable gear or worm reduction. The power required is about $\frac{1}{10}$ horse-power.

The main spindle carries a dog clutch normally in engagement and driving a cam. A roller bears on the upper surface of the cam, and is attached to the lower end of the rod *H*. It is guided so that it rises and descends at each rotation of the

cam. Fixed on the rod *H* is an arm *J* which engages with the lower face of the hammer *M* ; thus, when the rod *H* rises, by rotation of the cam, the hammer *M* is also lifted. The hammer slides freely between two sets of three-joint guiding screws, these screws being carried by the two castings seen attached to the standard *G* and its fellow on the opposite side.

Mounted upon the standard *G* is a sleeve *W*, free to rotate about the standard, but normally held in a fixed position by the spring *L*. Clamped on the sleeve *W* is an adjustable catch *K*. As soon as the arm *J* has lifted the hammer *M* sufficiently, the spring *L* causes a partial rotation of the sleeve *W*, so that, when the arm *J* again descends, the hammer is held by the catch *K*. The further descent of the arm *J* brings its lower inclined face in engagement with the roller arm *N*, attached to the sleeve *W*, in such a manner that the catch *K* releases the hammer *M*, allowing it to fall upon the test piece *O*.

The test piece, whose size and details are further discussed below, is carried by two hardened steel bushes in the Plummer blocks *PP*. It is rotated through 180° between successive blows. One end of the test piece is slotted to engage with a universal joint drive, and is kept in engagement by a screw *R*. The universal joint is driven, through a free wheel and clutch *T*, by the chain *S*. One end of the chain is attached to the roller, bearing on the cam already described, and the other end carries a weight suitably guided; the rotation of the test piece begins and ends entirely between the successive blows.

The revolutions of the test piece are recorded by a counter *V*, and, of course, the number of blows is found by multiplying the counter record by 2. When the test piece breaks, it comes in contact with an arm *X*, and thereby trips the clutch and stops the machine. The tank is partially filled with oil to provide efficient lubrication of the cam and other surfaces.

The hammer *M* is shod with a tup of hardened tool steel. The height of the drop depends on the position of the adjustable catch *K* on the sleeve *W*, and may be varied from about 1 to 4½ inches (25 to 113 millimetres). To allow a wide

range of tests, two hammers are provided, weighing 5 and 2 pounds (2·26 and 0·91 kilogrammes) respectively.

Using the 5-pounds hammer the main spindle may be driven at any speed up to about 60 revolutions, or with the 2-pounds hammer up to about 90 revolutions, per minute, giving 60 and 90 blows per minute respectively.

The machine is adapted for test pieces of dimensions similar to those adopted by Dr. Stanton; these are illustrated in Fig. 116. It will be seen that a V-notch is cut in the region of impact to localize the stresses. The angle at the bottom of the V is 90°, and is made as sharp as possible. As an alternative a semicircular groove, as shown in Fig. 116, B, may be used, and such a groove appears to offer several practical advantages over the V-groove. Referring to Fig. 116, A, it may be assumed that the action of the hammer, when it falls upon the test piece, is to produce a very slight but sudden bending at the section of smallest diameter—that is, at the bottom of the groove, as indicated diagrammatically in Fig. 116, D. This will produce an area of compression at *A*, and will tend to start slipping between the crystals, due to tension, at *B*. Of course the process is reversed at the next blow, because the test piece has been turned through 180° in the meantime.

It will be admitted that it is quite impossible to turn a groove having a true geometric angle; there must be some minute curve at the bottom of the groove. The size of this curve will determine the axial extent of the regions of compressive and tensile stresses. Since this size is in any case very small, with a nominally sharp V it is obvious that the variation between the size of curve in different test pieces will be relatively large, and will tend to introduce an element of uncertainty into the test results. It may be argued, in addition, that since no capable engineer would design a machine with a sharp re-entrant angle, the conditions of test are largely artificial.

Another shape of sample has been proposed, as shown in Fig. 116, C, having a relatively large portion of reduced diameter, but this is not advised. The end of the tup of the

hammer, being a plane surface, will bear upon the test piece for a considerable length parallel to the axis of the test piece,

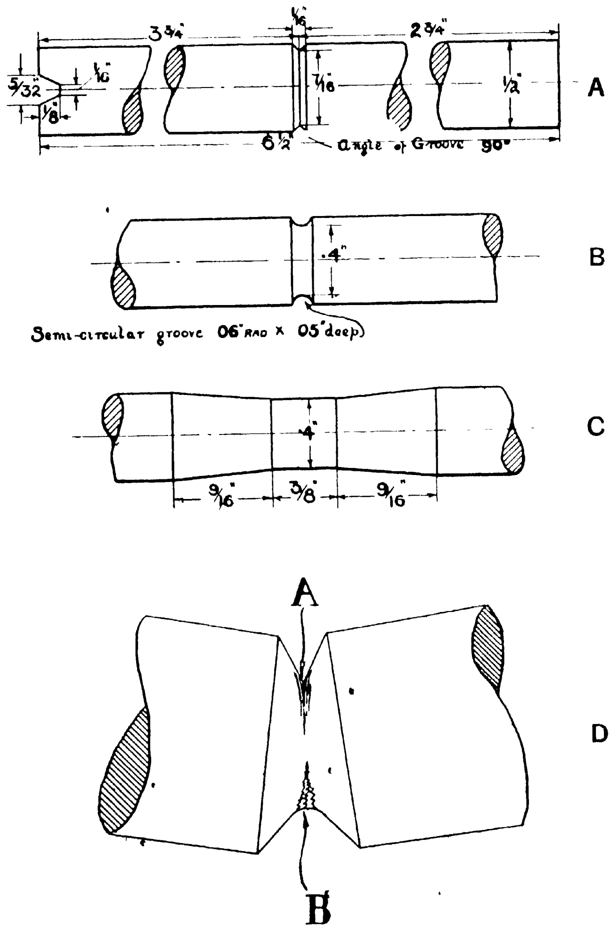


FIG. 116.

and it is probable that, owing to the minute bending of the test piece, the local stresses at the ends of the area of contact

are greater than at the plane equidistant between the points of support—in fact, it has been found that with test pieces of this shape fracture will begin at the point coinciding with the end of the area of contact between the tup and the test piece. There is a further disadvantage that the action of the blow will distort the cross-section of the material at the plane of fracture.

The results of tests upon mild steel specimens showed that the results were more consistent with semicircular than with V-grooves, the number of blows for fracture in the one case varying from 410 to 590 for different radii of grooves, and from 8 to 260 for the same V-groove. For the same radius of groove (viz., 0·06 inch) the variation was from 548 to 590.

Spring Testing Machines.

For statical tests of springs of different types machines of very simple design are now available, these, in general, consist of a screw or hydraulic loading device and a weighing apparatus similar to that employed upon tensile-testing machines. Means are provided for running on the load, usually by means of belt-driven pulleys and gearing, and gauges are fitted for indicating the deflections of the springs. Fig. 117 shows a typical form of static spring testing machine suitable for compression and tension springs of all kinds, including spiral and laminated leaf springs of railway and motor-car type. The load is applied by means of a square-threaded screw, provided with a level gearing, belt-driven, a ball-bearing thrust washer being provided to take the thrust of the screw. The deflection is measured by the movement of the screw itself.

The machine illustrated can be adapted to fatigue or shock tests by the provision of a belt-driven hammer action upon the spring whilst under an initial static load.

Machines have also been devised for testing springs with repeated loads, similar to those experienced in practice. This mode of testing springs is undoubtedly the more useful one, as it reveals the fatigue properties of the material and spring design qualities.

Fig. 118 illustrates a convenient repeated loading spring testing machine made by Messrs. Buckton and Company. This type is made in sizes for maximum loads of 12, 25, and 35 tons respectively, the corresponding movements of the reciprocating ram being 20, 22, and 22 inches respectively.

The maximum lengths of laminated springs provided for are 99, 99, and 110 inches respectively, and the maximum heights of same 30, 34, and 34 inches respectively. Coil springs can also be tested in these machines.

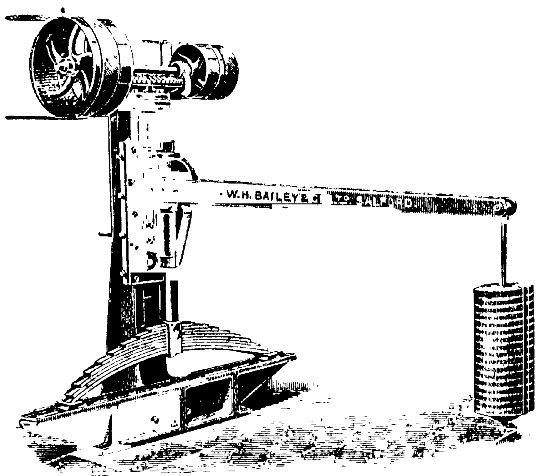


FIG. 117.—THE BAILEY SPRING TESTING MACHINE.

The load is applied to the spring by means of a powerful reciprocating ram, adjustable for position and length of stroke and actuated by a crank disc which is supported round the whole of its periphery. This disc is driven by means of a worm wheel of large diameter and a case-hardened steel worm from self-contained belt pulleys, a heavy flywheel being employed in the larger machines. A friction brake is provided for quickly stopping the machine. The weighing arm is fitted with roller carriages for supporting the ends of the laminated springs, and is provided with a wedging mechanism by means

of which its knife-edges may be relieved of the load during a repeated-loading test. An indicator is provided for showing the exact length of stroke of the reciprocating ram.

Fabric-Testing Machines.

For the purpose of making accurate tests upon cotton and woollen fabrics and similar materials it is necessary to

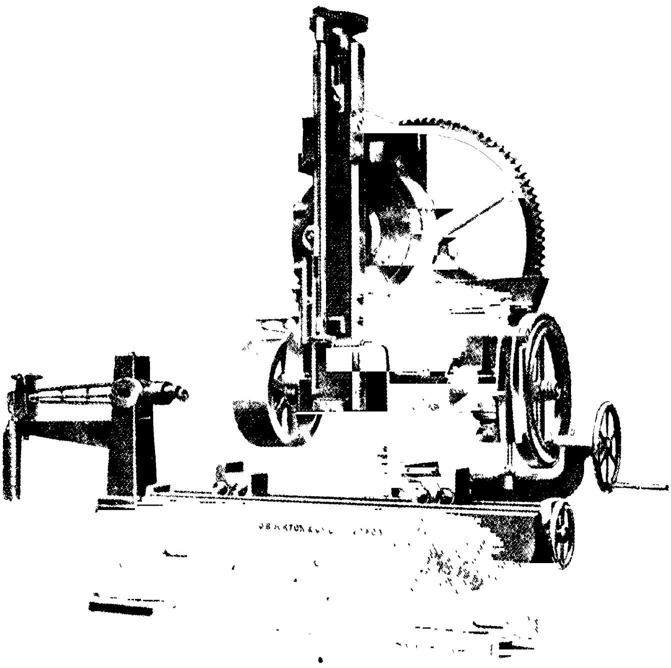


FIG 118.—THE BUCKTON VIBRATORY SPRING TESTING MACHINE.

apply the load at a given rate, and to know the value of the load, and the extension of the specimen at any moment during the test.

The Avery* testing machine, which is shown illustrated in Fig. 119, is very convenient for making tests upon fabrics

* Manufactured by Messrs. W and T Avery, Ltd , Birmingham

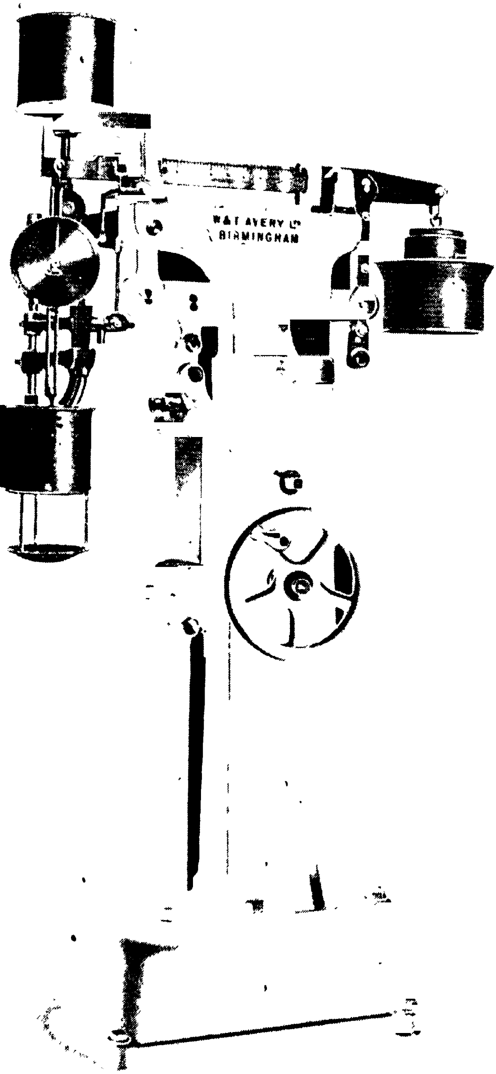


FIG. 119.—THE AVERY TEXTILE MATERIAL TESTING MACHINE.

of all kinds. In this machine lead shot is allowed to flow from the upper cylindrical receiver, supported on the fixed framing of the machine, into a receiver upon one end of the weighing arm. Gearing, hand operated, is provided for taking up the elongation of the specimen, and for balancing the load due to the falling shot.

The specimens accommodated in this machine can vary in length up to 28 or 30 inches, and in width up to 6 inches; they are held in corrrugated gun-metal clamps* by means of two milled clamping screws, and a universal joint is provided between the upper clamp and the weighing arm lever.

The weighing system consists of a main lever and a steelyard, both of which are of mild steel, fitted with bearings carried on the main standard.

The steelyard is graduated at both back and front. The front graduations range from zero up to 200-pound by 1-pound divisions. The graduations at the back of the steelyard range from zero up to 40-pound by $\frac{1}{5}$-pound divisions. The front graduations are for use when the machine is arranged with compound levers.

When more exact readings are required for smaller specimens, the weighing system is turned round upon the standard so as to bring the rear knife-edge of the steelyard directly over the specimen. The steelyard then acts as a single lever, and the back graduations are used.

The end of the steelyard is fitted with a hardened steel knife-edge, from which a receiver can be suspended.

A spring balance is interposed between the receiver and the steelyard, the dial of which is graduated to the maximum load—*i.e.*, up to 1200 pounds, by divisions of 5 pounds, and 240 pounds, by subdivisions of 1 pound, respectively. This enables the operator to read the approximate load on the specimen during the test. An upper reservoir is carried by the main standard, and fine shot is allowed to flow from this to the receiver. A graduated slide is inserted in the down tube to the reservoir, and is arranged to regulate the rate of flow of

* See Fig. 80, p. 182.

shot, so that the load is applied to the specimen at 500 pounds per minute, or as required.

A cut-off arrangement is provided by which the flow of shot is automatically cut off when the specimen breaks. This is operated by the steelyard when it falls to the bottom of the carrier. A baffle arrangement is also fitted to a bracket attached to the main frame. This diverts the flow of shot into a supplementary receiver at the side of the machine, whilst the steelyard is falling from its horizontal position towards the bottom of the carrier, thus preventing any increase of the strain until the steelyard is raised by taking up the elongation with the handle.

The baffle consists of a swinging portion, pivoted upon a bracket attached to the standard and balanced in either direction. A connecting-rod between the steelyard and the baffle causes the latter to swing with the rise and fall of the steelyard, thus diverting the flow of the shot over the dividing ridge of the fixed baffle either into the weighing or the supplementary receiver. When the steelyard reaches the bottom of the carrier, the cut-off arrangement is operated, completely shutting off the shot supply.

The object of the stretch balancing gearing is to enable the operator to take up the elongation of the specimen as the strain increases, so that the weighing system is kept in equilibrium.

It consists of a hand wheel gearing through bevel wheels and change gearing to a rotating nut which moves the straining screw in either direction. Two spindles are fitted, and the hand wheel can be fixed to either at will. A set of change wheels giving six different speeds is provided, the maximum and minimum being in the ratio of 36 to 1.

The method of making a test is as follows: The specimen being connected to the holders, the shot is allowed to flow from the reservoir into the receiver, and the elongation taken up with one of the changes of gear, thus keeping the steelyard floating index midway in the carrier. For low capacities a quick speed is used for the strain, and the weighing apparatus

is turned round, so that the steelyard can be used as a *single lever*. The maximum load in this arrangement is 240 pounds. For high capacities a slow speed is used, and the main lever and steelyard are compounded.

When the specimen has broken, the receiver containing the shot is emptied into the can suspended from the link-hanging from the rear knife-edge of the steelyard, and there balanced by means of the loose proportional weights and the sliding poise.

Hardness Testing Machine for Brinell Tests.

Fig. 120 illustrates a convenient form of lever machine for making Brinell tests, which possesses certain advantages over the ordinary hydraulic machines.

The specimen to be tested is placed upon the circular table, which is then screwed up by means of the handle shown near the table, until the hardened spherical ball is just in contact with the specimen. The load is applied by means of a cranked lever, through the worm, worm wheel, and screw shown in the diagram, under the specimen table.

To perform a test the specimen is placed upon the ball-seated table, and by throwing out a latch the worm is disengaged, thus allowing the worm wheel, which presses against a ball race, to be used as a hand wheel to quickly bring the specimen into contact with the ball; the latch is then thrown in and the worm engaged, load being applied by means of the cranked handle.

With the poise weight upon the beam set at either the 500-kilogramme or 3000-kilogramme position upon the scale of the steel arm, when this load is reached the beam raises in a gate, which is made "*open*" so that there is no possibility of the arm striking a top stop and thereby increasing the load. Pressure is then released and the specimen removed, the diameter of the impression being measured with a microscope, and the corresponding hardness number found from tables supplied.

In the hydraulic instrument a small hand pump supplies

oil pressure to the hardened ball plunger, and when the load is either 500 kilogrammes or 3000 kilogrammes, the oil pressure, acting upon a small accurately ground plunger, raises a corresponding weight* until it "floats"; an hydraulic pressure

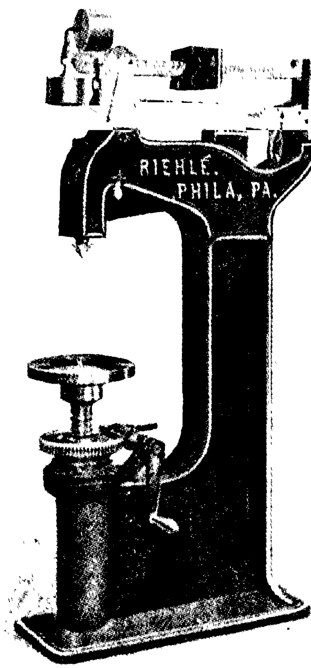


FIG. 120.—THE RIEHLÉ BRINELL HARDNESS TESTING MACHINE.

gauge is usually provided for giving a rough idea of the load upon the ball plunger. The lever form of machine is more simple and convenient to use, and can be readily calibrated.

* The ratio of the weight upon this plunger to the standard 500-kilogramme or 3000-kilogramme weight will be as the respective areas of the ball and floating plungers.

Machines for Testing Bearing Metals and Oils.

Special testing machines for determining the relative and absolute frictional and wearing qualities of white metals, bearing metal alloys, and oils, are now in fairly wide use, and it is possible to ascertain the wearing, frictional, and heating properties of bearing materials with them, under different conditions of pressure and rubbing speed.

In the case of a bearing metal it is necessary that it shall be able to withstand high bearing pressures at high rubbing speeds with the minimum of wear, and shall possess as low a coefficient of friction as possible; this latter condition ensures a minimum expenditure of power in overcoming bearing friction. It is also necessary that the heat conductivity of the material shall be high, in order to conduct away any heat that may be generated, apart from considerations of oil-supply.

Fig. 121 illustrates a convenient form of testing machine designed by Professor R. H. Thurston, and made by Sir W. H. Bailey and Company. Referring to this diagram, it will be seen that the machine is of the pendulum type, the weight of the pendulum *HJ* coming upon a bearing of the material to be tested, an independent shaft *A* through the bearings being belt driven by means of the pulleys *B*. The bearings *C* are split through their centre, and pressure is applied to the brass caps *D* by means of the spiral compression spring *L*, the amount of the pressure being regulated by means of the nut *I*. It is arranged that equal pressure is applied to both sides of the bearing by making the lower end of the spring act on the pendulum casing and thence upon the upper bearing, whilst the upper end of the spring acts directly upon the lower bearing. An indicating scale *N* shows the total bearing pressure, and, for standard bearings, the pressure per square inch.

The effect of bearing friction, when the shaft is running, is to tend to carry the bearing and its pendulum attachment around with it, until the moment of the displaced pendulum weight equals the frictional moment.

Thus, if d=diameter of bearing in inches, P=total pressure on bearing in pounds, R=distance in inches of the C G. of pendulum from the centre of bearing, W= weight of pendulum, and θ=arc of swing when shaft is running,

$$\text{Then Moment of Friction } = \mu \cdot \text{P} \cdot \frac{d}{2} \text{ pounds inches,}$$

$$\text{And Moment of Pendulum} = \text{WR} \sin \theta \text{ pounds inches;}$$

$$\text{Whence the Coefficient of Friction } \mu = \frac{2\text{WR} \sin \theta}{\text{P} \cdot d}.$$

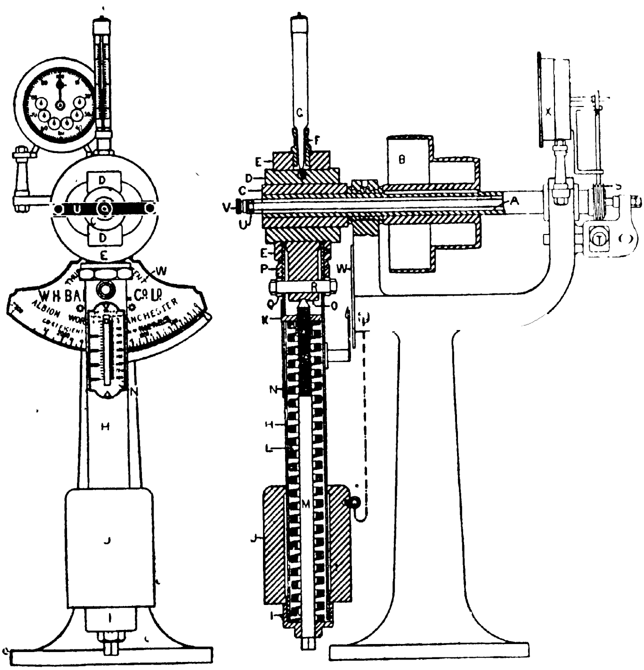


FIG. 121.—THE BAILEY-THURSTON OIL AND BEARING METAL TESTING MACHINE.

The pendulum arc scale can then be graduated in terms of the coefficient of friction for a definite load P. In the machine described the coefficient of friction is equal to the arc scale

reading divided by the total pressure (which can be read off the scale N).

The temperature rise of the bearing may be read off the thermometer G, the bulb of which is immersed in a mercury-filled recess in the bearing D.

The total number of revolutions and the rate of revolution made by the shaft can be read off a tachometer or speed indicator X.

In one form of Thurston tester a continuous record of the movement of the pendulum arc is made during a test, so that variations in the coefficient of friction can be readily followed. The rubbing speeds can be varied up to 736 feet per minute. In endurance tests it is usual to ascertain the variations of temperature and coefficient of friction during the period of the test, and to measure the amount of wear by weighing the bearings both before and after the test; in each case the bearings are well washed in petrol before weighing. In the Cornell* oil and bearing testing machine, the journal measures $3\frac{3}{4}$ inches diameter by $3\frac{1}{2}$ inches long, giving 7 square inches projected area; a maximum load of 700 pounds per square inch can be applied, the total load being measured by a weighing arm and travelling jockey weight. The wear is ascertained after a run of one million revolutions at rubbing speeds up to 500 feet per minute

Other Methods of Stress Determination.

In numerous examples occurring in practice it is inconvenient, expensive, or impossible to determine the behaviour of certain members, bodies, or structures under loads applied in testing machines, so that indirect methods have to be devised.

The method of making a scale model of the structure in the same material and loading same under similar conditions has already been mentioned.†

* Made by Messrs. Olsen, of Philadelphia.

† See p. 3.

In certain instances much useful information can be obtained by making small-scale models of beams, struts, and ties, and measuring the deflections under loads and noting their manner of failure.

Scale-Model Tests.

The author has made a number of scale-model tests upon built-up struts and aeroplane wing spars by employing good-quality Bristol board, and was able to predict with accuracy the breaking loads of the full-sized members, which were subsequently made and tested to destruction. From preliminary direct tensile and compressive tests the ultimate strengths were known, and the crippling and buckling loads were referred to these values. The manner in which different designs of built-up struts and beams failed was investigated, and places of weakness were strengthened until the maximum strength for weight was attained. It was generally found that in built-up sheet-metal members there is a definite relation between the thickness of metal and the dimensions of the sides or cross-section for maximum strength for weight. Buckling and secondary flexure occur at considerably smaller values of the compressive stress than the true ultimate value, and in such cases, where the thickness of the walls or sections is not sufficient, the ordinary methods of calculating working stresses do not apply.

The Strain Method.

The stresses in certain complex structures may often be deduced from measurements of the strains in different directions when loads are applied. An example* of the principle involved is illustrated in Fig. 122, which shows the values of the stresses at different distances from the neutral axis of a rolled-steel I beam under load, as deduced from extensometer measurements of the stresses. In this case the bending moment was uniform over the length of beam investigated, and

* From "The Measurements of Stresses in Materials and Structures," by E. G. Coker, Cantor Lectures, 1914.

the stresses were within the elastic limit. The value of the elastic modulus for the steel used was $3 \cdot 1 \times 10^7$ pounds per square inch; obviously this method is only directly applicable to materials obeying Hooke's law of elasticity, unless the stress-strain relation is known.

The strain method has been applied to determine the stresses in bridges, ships, boilers, and in similar cases; in all such cases it is necessary to measure the strains over as short a length as possible, otherwise the average stresses deduced will be the values over a distance.

For complex structures and for surfaces of various shapes, such as boilers, it is often convenient to use mirrors attached to the surfaces, and to arrange for their angular changes to be

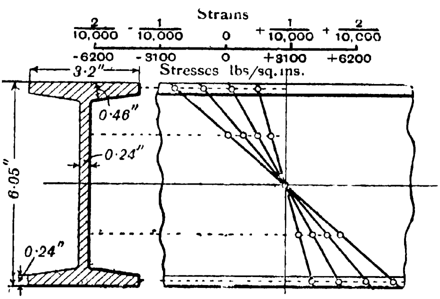


FIG. 122.

measured by means of reflected rays of light moving along a scale, or by telescopic observation; strains should be measured in at least two different directions.

Another method of studying the behaviour of members and bodies under load is to make a scale model in india-rubber, and to measure the strains in different directions under load; it is well known that the distributions of stress in different elastic bodies of similar shape are the same within the elastic limits, so that the stress distribution in a body is deducible from that measured in a scale model of another elastic substance.

When india-rubber is employed,* owing to the slowness

* Also see Vol. II., Chapter X, for the mechanical properties of rubber.

(usually several hours) with which the material yields or recovers, sufficient time must be allowed before the strains or deformations are measured.

From measurements of the strains in the directions of the principal stresses—that is to say, from the values of the maximum and minimum strains—the values of the principal stresses p and q may be inferred from the relations—

$$p = E\,(e_1 - \sigma e_2) \qquad - \quad - \quad - \quad (1)$$
$$q = E\,(e_2 - \sigma e_1) \qquad - \quad - \quad - \quad (2)$$

where E is the elastic modulus, σ is Poisson's ratio,* and e_1 and e_2 the principal strains.

In the case of flat-surfaced members the values and directions of the principal strains may be obtained by marking the surface with circles of appropriate size before loading, and measuring the axes of the elliptical shapes resulting from the load application. The surface, thus marked, may be photographed before and after loading.

This method has been applied† to determine the relative values of the stresses across a tension member having holes drilled in it; the effect of the presence of holes upon the stress distribution will be seen from Fig. 123 to be very marked.

Near the edges of the holes the tensile stress is greatly increased, and there is a transverse compressive stress due to the rivet resistance.

The problem of the stress distributions in masonry arches and dams has been studied experimentally by means of strain measurements from scale models made of an easily deformable substance under light loads, such as rubber

The Thermal Method.

Another method occasionally employed for determining the stress at a given point (as distinct from the value deduced from the strain over a definite distance) depends upon the change of temperature resulting when stress occurs; within

* See p. 11.

† By Messrs. Wilson and Gore. *Vide* Cantor Lectures, 1914.

the elastic limit there is a fall in temperature which is proportional to the tensile stress applied and to the coefficient of expansion, according to the relation—

$$t = -\frac{\mathrm{T}}{\mathrm{J}} \cdot \frac{\alpha}{s\rho} \cdot p,$$

where t is the small fall in temperature accompanying a small tensile stress increase p, T the normal temperature (absolute)

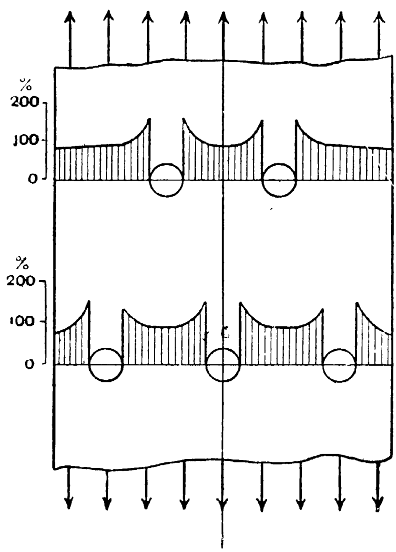


FIG. 123.—THE STRESSES IN DRILLED PLATES.

at the spot, α the coefficient of expansion, J the mechanical equivalent of heat, s the specific heat at constant pressure, and ρ the density.

The change in temperature is, however, very small for ordinary stresses, being about 0·12° C. per 10,000 pounds per square inch for steel, so that accurate methods of temperature measurement have to be used. Thermo-electric couples such as those of bismuth-antimony, employed with suitable galvano-

meters, can be made to indicate temperatures to 0·001° C., and are therefore generally employed for this purpose.

Beyond the elastic limit in tension there is a more marked temperature rise, which necessitates the use of a different temperature scale; the shear stress, moreover, within the elastic limit does not appear to be accompanied by any temperature change, so that this somewhat simplifies matters. This method, which is, however, not a convenient (although a useful laboratory) one for commercial purposes, has been used* to determine the stress distributions in model beams, girders, and joists of various sections.

Optical Stress Determination Methods.

An interesting optical method of determining stresses is based upon the discovery of Sir David Brewster's in 1816 that when a beam of plane polarized light is passed through a stressed transparent plate or body, and the beam is viewed through a Nicols prism or projected through same, a remarkable colour effect is apparent, from which the directions and intensities of the principal stresses may be deduced.

This method has of late years been developed and utilized for the solution of complex stress problems by Coker,† Filon,‡ A. R. Low,§ and others.

The effects observed depend upon the property acquired by the transparent material, under load, of doubly refracting the light passing through it. The effects are not observed in the case of ordinary light, which may be regarded as consisting of transverse vibrations in all planes, and in order to examine the effects of double refraction it is necessary to rob the light of all of its transverse vibrations except those in one plane

* See "The Measurement of Stresses in Materials," by E. G. Coker, p. 15, Cantor Lectures, 1914, *Journ. of Roy. Soc. of Arts.*

† *Engineering*, January 6, 1911; March 3, 1912; December 13, 1912; March 28, 1913; Cantor Lectures, 1914. "Photo-Elasticity for Engineers," Proc. Inst. Autom. Engineers, November, 1915.

‡ *Phil. Mag.*, 1912, and Proc. Camb. Phil. Soc., vols. xi. and xii.

§ "Stress Optical Experiments," by A. R. Low, *Aeron. Journ.*, December, 1918.

by passing the beam through an Iceland spar prism. Fig. 124, which is reproduced from Professor Coker's paper of November, 1917 (reference to which is given in the footnote on p. 244), will serve to briefly explain the principles involved.

The beam of light is caused to pass through a prism of Iceland spar *A*, cut in a particular manner; this prism polarizes the light—that is, it allows only those transverse vibrations parallel to its principal plane to pass through it—so that the emerging beam *B* has transverse vibrations in one plane only. *C* denotes a piece of transparent material stressed in its plane, which is normal to the beam of light, and the effect of passing a beam *B* through such a plate is to divide it up into two plane polarized waves *D* and *E*, which have the same directions as those of the principal stresses in *C*, but which differ in phase by an amount which is proportional to the difference between

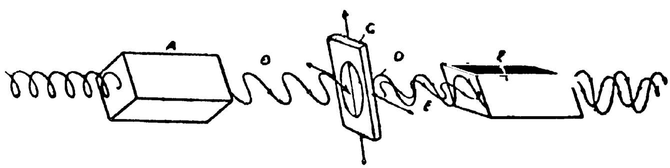


FIG. 124.—THE PRINCIPLE OF THE OPTICAL METHOD OF STRESS DETERMINATION.

the principal stresses p and q, in the transparent stressed material, to the thickness of the stressed plane, and to the particular material employed. In order to observe the optical effects of these two mutually perpendicular transverse wave systems, a second polarizing prism *F* is employed, having its principal plane at right angles to that of *A*.

The interference effects of the two wave systems *D* and *E* are then observable by the increased intensity of the light at some places of the stressed plate and by the decreased intensity of other places, when a beam of unicoloured light is used. When the stressed plate is viewed with ordinary white light, the mutual interference of the waves *D* and *E*, after passing through the polarizer *F*, is evident in the marked colour effects seen over the stressed specimen.

The dark spots produced when the specimen is viewed through a polarizer occur at places where the directions of principal stress correspond to the principal planes of the polarizers *A* and *F*. By rotating the mutually at right angles combination *A* and *F* the whole specimen may be mapped out into a series of dark spots or lines, denoting the positions of the axes of principal stress for the whole of the specimen; in this manner the principal stress directions can be obtained for the stressed specimen.*

This method of ascertaining the stress distribution has been shown to give reliable results when the elastic properties of the transparent material are similar in effect to those of the metal to be investigated. For metals such as steel and iron, which vary from the elastic to the plastic states when stressed beyond the elastic limit, nitro-cellulose is a good optical material. For brittle metals, such as cast iron or hardened steels, glass is suitable, as it possesses similar elastic properties.

This optical method has been successfully applied to the experimental solution of the problem of the stresses over a drilled plate tested in tension, to the stresses in loaded hooks and rings, the stresses in loaded crank-shafts, to the distribution of stress in a large compression block loaded over a relatively smaller definite area, and in the design of the eye-pieces of tension members or stays.† The reader is referred to the original papers for a full account of these interesting experiments, the results of which throw much light upon hitherto obscure problems.

Fig. 125 shows the values of the tangential stresses at the boundary lines of a drilled flat plate tension specimen obtained by the above method; the height of the ordinates normal to

* The actual values of the stresses may be determined by comparing the observed colour intensities with those of a strip or block of similar material under simple tension or compression of known amount, placed alongside the member in question, and viewed with the same optical apparatus.

† Also to the problem of the determination of stresses in aeronautical structures. "Stress Optical Experiments," A. R. Low, *Aeron. Journ.*, December, 1918.

the boundaries is proportional to the tangential stress occurring there. The marked increase in tensile stress in the vicinity of the section through the hole perpendicular to the

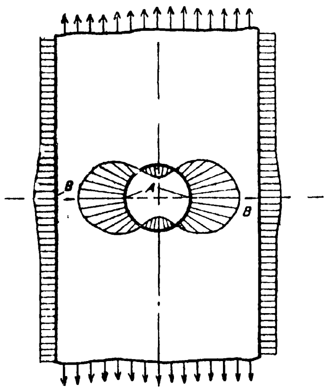


FIG. 125.—TANGENTIAL STRESSES IN DRILLED TENSION MEMBER.

line of pull will be noted, and also the compression stress at the top and bottom of the hole.

Fig. 126 shows the lines of the principal stresses in the pre-

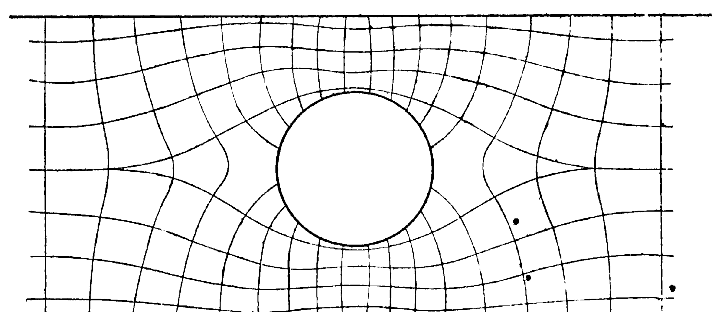


FIG. 126.—PRINCIPAL STRESSES IN DRILLED TENSION MEMBER.

ceding case, as mapped out by the optical method described; it will be seen that the lines approach one another at the minimum section, and that they are also spaced unequally.

Where the lines are close together there is a higher intensity of stress; for example, at the boundary of the hole. It will be noted that everywhere the two sets of stress lines are mutually normal, wherever they intersect.

Fig. 127 shows the stresses at the fillets of a loaded crank-shaft obtained by the optical method, the intensities of the

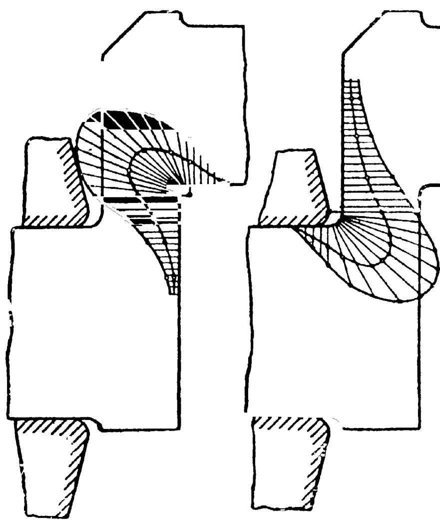


FIG. 127.—STRESSES IN CRANK-SHAFT FILLETS.

stresses being found by placing a tension member across or along the contour and loading it until a black field is produced; this is an indication of the stress equality in the two members. The two sets of lines, or curves, shown in the diagrams are for a single and a double load, respectively; the values of the maximum stresses at the two places shown are greater than those calculated upon the ordinary beam assumptions.

CHAPTER IV

THE METALLOGRAPHY OF FERROUS MATERIALS

Iron and Steel.

THE present considerations will be chiefly confined to the actual commercial properties of the ferrous metals, and to their heat treatments and processes; it is not proposed to go into the questions of the metallurgical and chemical operations connected with the extraction and smelting of the ores, methods of production and derivation of the metals, and similar operations, but rather to consider the constitution and properties of the resulting products from the point of view of the application, treatment, and testing of same.

Classification of Ferrous Metals.

It is of essential importance to distinguish between the three principal products derived from iron ores—namely, wrought iron, steel, and cast iron.

Wrought iron,* as used commercially, is usually defined as slag-bearing malleable iron, practically free from carbon, which does not harden appreciably when heated to a red heat and suddenly cooled or quenched.

The term " **steel** " is applied to iron containing from about 0·2 and up to about 2·2 per cent. of carbon, which is malleable in some one range of temperature, and which is capable of hardening by heating and quenching; it may be cast, initially, into a malleable mass (as in the case of cast steel).

Steel also includes iron alloys *containing carbon*, with other elements, such as nickel, manganese, tungsten, chromium, and vanadium, which fulfil the conditions above defined.

* For fuller particulars of its properties, see p. 289.

Cast iron is non-malleable iron containing much carbon, usually from about 2·2 to 5·0 per cent., and which does not harden appreciably when heated and quenched.

Malleable cast iron* is a malleable iron obtained by treating cast iron without fusion.

The following table,† represents in convenient form the generally accepted classification of ferrous metals:

TABLE XLIII.

CLASSIFICATION OF STEELS AND IRONS.

	Containing very little Carbon (less than about 0·3 *per cent.).*	*Containing an intermediate quantity of Carbon (from about* 0·3 *to* 2·2 *per cent.).*	*Containing much Carbon (from about* 2·0 *to* 5·0 *per cent.).*
Slag-bearing or Weld Metal Series.	*Wrought Iron.* Puddled and bloomary, or charcoal hearth iron belong here.	*Weld Steel.* Puddled and blister steel belong here.	
Slagless or Ingot Metal Series.	*Low-Carbon or Mild Steel (sometimes called Ingot Iron).* May be either Bessemer, open hearth, or crucible steel.	*Half Hard and High-Carbon Steel (sometimes called Ingot Steel).* May be either Bessemer, open hearth, or crucible steel. Malleable cast iron also often belongs here.	*Cast Iron.* Normal cast iron, "washed metal," and most "malleable cast iron" belong here.
		Alloy Steels. Nickel, manganese, tungsten, chromium, and vanadium steels belong here.	*Alloy Cast Irons.* Spiegeleisen, ferro-manganese, and silico-spiegel belong here.

Microscopic Examination of Metals.

There are three principal methods‡ of examination of metals now in vogue—namely: (1) The Mechanical Test Method;

* See Chapter V.

† "Ency. Brit.," 10th edition, vol. ix., p. 571.

‡ As distinct from the X-ray method described on p. 254.

(2) The Chemical Analysis Method; and (3) The Metallographic or Microscopic Structure Examination Method.

The first of these methods has already been dealt with in the preceding chapters; the second one belongs more to the domain of chemistry, and is based upon the results of analyses of metals; the latter method comprises an actual microscopic examination of the structures of the metals.

Each method has its own sphere or field of usefulness, and in a large number of cases the methods are interrelated; for example, it is well known that the mechanical properties of metals and alloys depend upon their chemical composition. Apart from the chemical constitution, it is also of great importance to know the manner in which the chemical elements are combined among themselves, for metals of the same chemical composition often differ widely in their mechanical properties; for example the properties of a given cast steel vary considerably with its mode of heat treatment, the hardening and tempering processes.

It is here that metallography plays an important part, for it enables the actual structural constitution of the metals to be studied in detail, and affords explanations of hitherto obscure facts. For example, the causes of failure or fracture of metals under the action of stresses can be readily detected, even when there exists no knowledge of these stresses; or, again, the exact effects of such processes as heating, hardening, and annealing upon the arrangement of the particles constituting the metal, and upon the subsequent strength of the metal, can be definitely stated.

Defects in metals due to incorrect heat treatment, overheating, excessive rolling or drawing, foreign matter, overstrain, and other causes, can be readily detected without the employment of expensive chemical and mechanical methods.

Further, the effect of different amounts of carbon, phosphorus, and sulphur in cast iron and pig iron can be readily examined, in reference to the constitution of the resulting metal.

Preparation of Specimens for Microscopic Examination.

In the case of metals which have failed in actual use, the specimens should be obtained as near the fracture position as possible.

It is often useful to make a preliminary visual examination with the aid of an ordinary pocket lens, in order to trace zonal lines, places of growth of the fracture, slipping or relative sliding, and to determine whether the fracture is coarse or finely crystalline.

The specimens, which should measure about 1 inch square and ¼ inch thick, must be cut in two directions mutually at right angles.

These specimens are next polished in a series of progressive steps, commencing with a file or by initial flat grinding, followed by coarse emery paper, smoother emery, and so on, down till the finest 0000 paper is reached; the next stage of fine polishing is then usually followed with the aid of a wheel covered with two layers of thick khaki cloth, with a layer of diamantine or similar polishing powder between, using a securing ring to hold the layers together. The specimen is then held against and moved across the wetted surface of the cloth whilst the wheel rotates at about 1000 r.p.m.; the pressure upon the specimen is gradually reduced until a satisfactory polish is obtained. Hard metals are more easy to polish than soft metals, which are sometimes cast upon glass or mica sheets, instead of polishing. Special polishing machines, such as the Stead machine, are now available for this purpose; but hand polishing, if done properly, gives excellent results.

The specimens can now be directly examined under a microscope with objectives giving a series of magnifications from about 20 up to 2000 diameters, for the detection of impurities such as slag, porosities, sulphides, etc.

For the examination of the constitution of the metal it is necessary to employ special etching reagents, each depending upon the nature of the constituent it is required to investigate.

The principle of most etching reagents is that they act as solvents, attacking certain of the constituents of the metal more readily than others, or that they refuse to attack one

or more of the constituents, thus leaving these in "relief," or that they dissolve away the joints between adjacent grains or crystals. In some cases the reagent colours one of the constituents differently from the others.

The etching reagents of the solvent type employed include nitric acid, sulphuric acid, hydrochloric acid, alcohol solutions, ammonia, sodium hydrate, etc.

For example, the structure of pearlite in steel may be developed by using an etching reagent of 5 per cent. picric acid in alcohol; whilst the difference between brittle and non-brittle steels can be readily detected by using a 4 per cent. solution of nitric acid in iso-amyl-alcohol.*

Another method of preparing polished specimens is known as the "*polish attack*" one, and consists in polishing upon a piece of wet parchment, held on a piece of wood, and moistened with a 2 per cent. solution of ammonium nitrate; precipitated chalk is also used to facilitate the polishing process. An aqueous extract of liquorice-root is also employed for the polish attack method, which has been successfully applied to the examination of steels for cementite, pearlite, sorbite, martensite, etc.

The method of "*bas-relief*" polishing consists in polishing upon a soft ground, such as leather, cloth, or rouged parchment, so that the softer constituents wear away and the harder ones stand out, polished in relief. This method yields good results in the detection of troosite, martensite, and pearlite.

Another method, known as "*heat-tinting*," depends upon the fact that the different constituents when heated become differently tinted or coloured, the more oxidizable ones being coloured by the oxide tints. This method has been largely used by Stead, and is employed for detecting the presence of sulphur and phosphorus in irons and steels.

X-Ray Examination of Metal Structures.

An interesting and, at the same time, very important method has recently been developed, and has been adopted by

* For fuller particulars of various etching solutions and methods see "The Microscopic Analysis of Metals," pp. 114 and 134, by F. Osmond and J. E. Stead.

several of the leading Continental and American engineering firms, for examining the structure of metals by means of a new type of X-ray apparatus.*

With this system it is possible to detect flaws in a steel block of 4 inches thickness as small as $\frac{1}{64}$ inch in diameter, and to photograph the internal structure of component pieces, such as sparking plugs, engine cylinders, shell fuses, etc., with the accuracy of a draughtsman's drawing. It is also possible to detect differences of $\frac{1}{1000}$ inch in mica insulators. The most important application of this system, however, is in connexion with the examination of metals, the detection of air bubbles, flaws, blowholes, and similar defects in castings.†

The method adopted employs a new type of vacuum tube invented by Dr. Coolidge, which possesses a vacuum about 1000 times greater than the ordinary X-ray tube, and which requires a working voltage up to about 250,000 volts, associated with a current of only from 1 to 3 milliampères.

The principle of the Coolidge tube is somewhat similar to that of the wireless thermo-valve; the ordinary X-ray tube discharge is increased to a considerable extent by making the cathode of a spiral of tungsten surrounded by a sleeve of molybdenum so as to focus the cathode stream. When the tungsten cathode is heated by means of a battery a stream of negatively charged electrons is emitted, the intensity of which can be regulated by means of the heating device. The anode during the exposure becomes very hot, and for rapid work it is necessary to have a water-cooled anode.

The method of working is a photographic one, the object to be examined being placed beneath a photographic plate, and the X-ray beam directed through the metal object from the opposite side. By means of a special intensifier screen the exposure ordinarily necessary can be reduced by from 95 to 96 per cent. The ordinary rate of working is such that it is

* For fuller particulars *vide* the Proceedings of the Röntgen and Faraday Societies, April, 1919 *et seq*, and "The Examination of Materials by X-Rays," *Engineering*, May 2, 9, and 16, 1919.

† This method is now employed for the internal examination of aircraft timber parts, such as glued or taped spars, plywood, hollow-members, etc., and for welded joints, etc.

possible to make sixty radiographs in a quarter of an hour; but very stringent precautions have to be taken to protect the operator from "X-ray burns." He is placed in a special cabinet thickly lined with lead, and in another room the apparatus (also enclosed in a thick lead case), is placed.

Constitution of Ferrous Metals.

The results of microscopical examination and chemical analysis have shown that most metals have a constitution resembling the igneous and metamorphic rocks,* consisting of an aggregation of minute crystalline fragments or particles of two or more elements or substances; each particle has a definite entity, chemical composition, and physical properties; there are, further, different structure arrangements in different metals, corresponding, in the case of rocks, to the granitic, obsidian, schistose, and other types.

It has also been conclusively demonstrated that the constituents of metals and alloys behave in a similar manner to those of liquid solutions; for example, steel containing less than 0·9 per cent. of carbon, and at a temperature exceeding 700° C., is a homogeneous solid solution of iron carbide (Fe_3C), known as *Cementite*, in an allotropic form of iron. When this solution is slowly cooled down it deposits pure iron, until at a certain temperature—namely, at about 670° C.—it solidifies into an "eutectic" or metallic mixture having a definite composition. If the original molten steel had consisted of more than 0·9 per cent. of carbon the iron carbide would have solidified first, as cooling occurred, and at 670° C. the "mother liquor," or pure iron, would have solidified. The resulting mixture would then have possessed a different constitution.

Definitions of Constituents.

It may be as well, before proceeding further with the subject of solid solutions and thermal changes, to define the different microscopic constituents of irons and steels which commonly occur. These may be classified into six principal

* These materials, like most metals, have been formed from the cooling of molten masses.

types and five other ones of lesser importance. The former series consists of: (*a*) Ferrite, (*b*) Cementite, (*c*) Pearlite, (*d*) Martensite, (*e*) Austenite, (*f*) Troosite. Other constituents, including Hardenite and Sorbite, have also been found.

The second series comprises the three allotropic forms of nearly pure iron, graphite, and slag.

(*a*) **Ferrite** is the name given to what is probably pure iron grains or crystals, which are very soft and ductile. These crystals are chiefly fragments of cubical crystals which develop

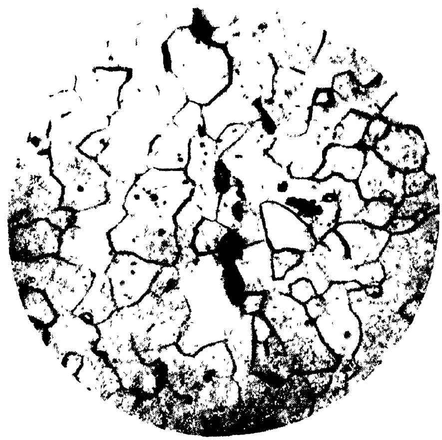


FIG. 128.—NEARLY PURE IRON, SHOWING FERRITE AND SLAG INCLUSIONS (DARK PATCHES). × 100.

around independent centres of solidification, and are mutually limited by roughly plane surfaces. Low carbon steels and wrought iron consist chiefly of ferrite.

Fig. 128 shows the ferrite grains in carbonless iron, the dark spots being slag impurities.

(*b*) **Cementite.**—This is a definite carbide of iron (Fe_3C) which is extremely hard, being harder than ordinary hardened steel or glass. It is considered to be as hard as *felspar* (No. 6 on Moh's* scale of hardness). This hardness property enables

* See p. 143

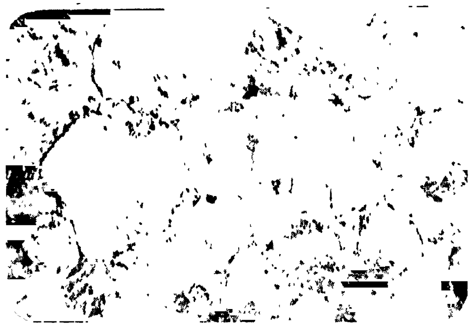


FIG. 129.—STEEL CONTAINING ABOUT 1·1 PER CENT. CARBON, SHOWING PEARLITE AND CEMENTITE. × 400.

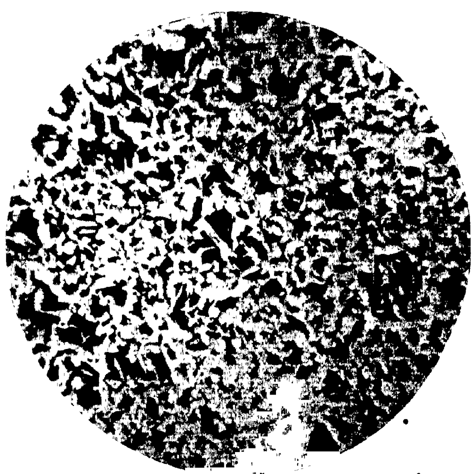


FIG. 130.—0·1 CARBON STEEL (MILD). ETCHED. × 100.

cementite to be readily detected and isolated by bas-relief polishing.

Cementite increases generally with the proportion of carbon present, and the hardness and also the brittleness of cast iron is believed to be due to this substance.

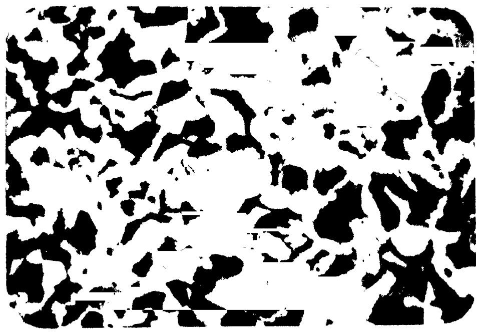


FIG. 131.—STEEL CONTAINING 0·40 PER CENT. CARBON, SHOWING PEARLITE AND FERRITE. × 400.

FIG. 132.—0·60 CARBON STEEL, FORGED CONDITION. ETCHED. × 100.

Fig. 129 shows the cementite and pearlite in 1·1 per cent. carbon steel.

(*c*) **Pearlite** is the name given to a mixture of ferrite and cementite, which occurs more particularly in medium and in low carbon steels in the form of fine lamellæ, which are usually

curved and interstratified with those of ferrite. This mixture derives its name from the fact that it shows, with oblique lighting, under the microscope the rainbow colours of the mother-of-pearl when the etching or polishing process has removed part of the surrounding softer ferrite.

Fig. 130 shows the darker patches of pearlite and the lighter grains of ferrite in the case of mild carbon steel. Figs. 131 and 132 show the ferritic and pearlitic structure of 0·40 and 0·60 carbon steel respectively.

It has been found that the proportion of pearlite increases from nothing in the case of pure carbonless iron up to 100 per

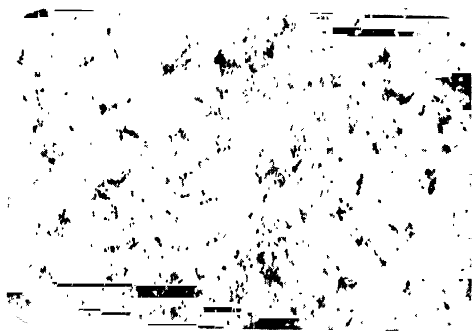


FIG. 133.—STEEL CONTAINING 0·9 PER CENT. CARBON, PRACTICALLY ALL PEARLITE. × 400.

cent., or saturation, for steel containing 0·90 per cent. of carbon as shown in Fig. 133; thus a 0·3 per cent. carbon steel will consist of about 33 per cent. pearlite, and the rest ferrite. Table XLIV. on p. 260 shows the relative proportions of pearlite and ferrite in carbon steels. It is, then, characteristic of soft steels that they contain ferrite and pearlite, and that the hardness increases with the proportion of pearlite.

Hard steels are mixtures of pearlite and cementite.

In all cementation steels and steels cooled very slowly the cementite aggregates in particles of the largest size, and is therefore more readily discernible.

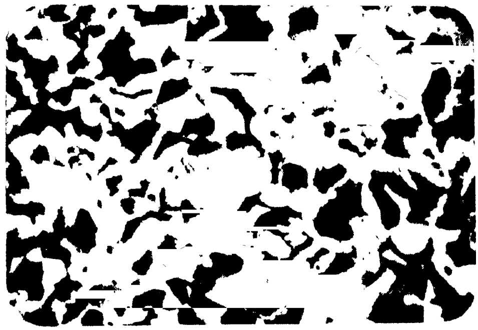


FIG. 131.—STEEL CONTAINING 0·40 PER CENT. CARBON, SHOWING PEARLITE AND FERRITE. × 400.

FIG. 132.—0·60 CARBON STEEL, FORGED CONDITION. ETCHED. × 100.

Fig. 129 shows the cementite and pearlite in 1·1 per cent. carbon steel.

(*c*) **Pearlite** is the name given to a mixture of ferrite and cementite, which occurs more particularly in medium and in low carbon steels in the form of fine lamellæ, which are usually

quenching of high-carbon steel from a slightly higher temperature than the maximum temperature of the critical interval.*

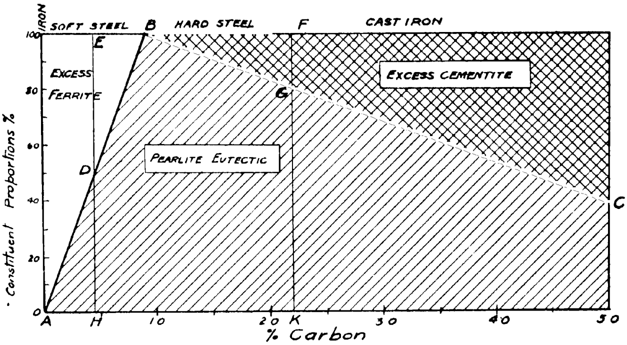


FIG. 134.—IRON CARBON COMPOUNDS.

FIG. 135.—HARDENED AIR-HARDENING STEEL. ETCHED. × 500.

Martensite is found in the carbonized regions of case-hardened soft steels, hardened by quenching, but with the lower proportions of carbon the needles are longer and more definite. Fig. 135 shows the martensitic-like structure of

* See p. 266.

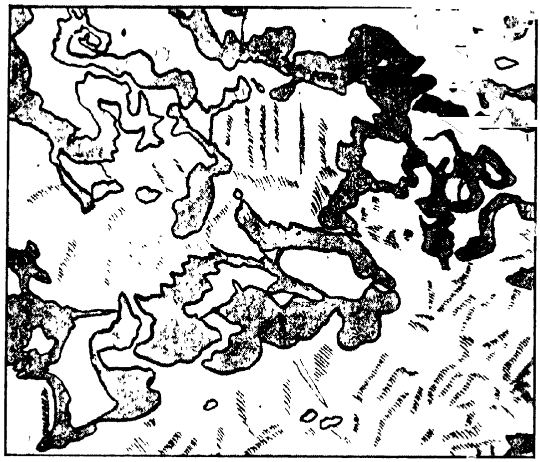


FIG. 136.—TROOSITE AND MARTENSITE IN 0·45 PER CENT. CARBON STEEL. × 800.

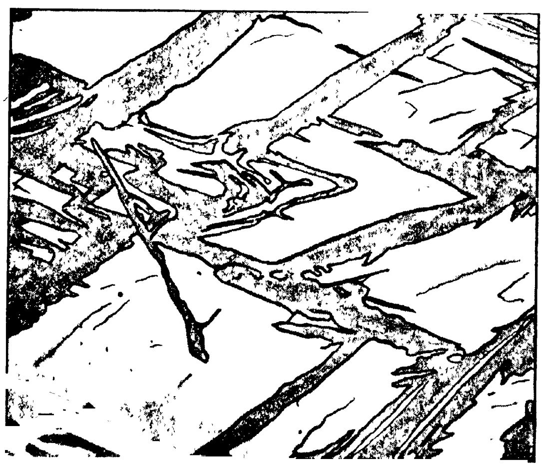


FIG. 136A.—AUSTENITE AND HARDENITE IN 1·57 PER CENT. CARBON STEEL. POLISH ATTACK. × 800.

hardened air-hardening steel, and Fig. 136 shows the chief characteristics of this type of structure.

(*e*) **Austenite** is another constituent of steel, obtained when carbon steel containing more than 1·10 per cent. of carbon is heated above 1000° C. and quenched at about 0° C. It is softer than martensite, and can be scratched with an ordinary sewing-needle; it usually occurs as a mixture with martensite or hardenite.

The amount of austenite increases with the amount of carbon from nothing at 1·1 per cent. carbon up to about 70 per

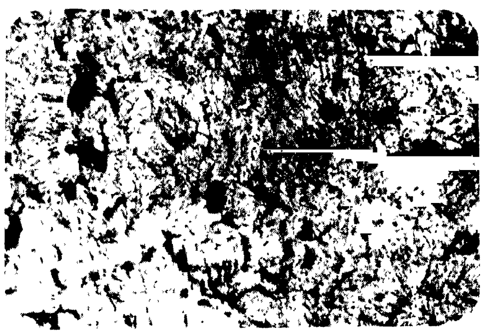


FIG. 137.—QUENCHED CARBON STEEL, SHOWING BACKGROUND OF SOLID SOLUTION WITH COMMENCEMENT OF DECOMPOSITION SHOWN BY THE BLACK PATCHES OF TROOSITE. × 400.

cent. at from 1·6 to 1·8 per cent. carbon; beyond this point it produces a separation of cementite, and therefore no longer increases.

(*f*) **Troosite** is obtained by quenching steels during the critical interval* or transformation period. It occurs as a slightly granular, almost amorphous, and mammillated structure, and in quenched steel (from the critical interval), it replaces the ferrite, and is surrounded by another constituent known as *Sorbite*.

Fig. 137 shows the structure of a quenched high-carbon steel, showing the background of solid solution, with commencement of decomposition shown by the presence of troosite (black).

* $Ar_{1 \cdot 2 \cdot 3}$.

Allotropic Forms of Iron.

There are at least three allotropic modifications in the case of pure iron—namely, α iron, β iron, and γ iron, each of which has a corresponding temperature range.

α **iron** is the weak, ductile, magnetic variety, stable only below the Ar. 2 point (Figs. 138 and 144) and is characteristic of ordinary wrought iron and low-carbon steel.

β **iron** is the non-magnetic kind, and is believed to be very hard and brittle, and is probably characteristic of certain self-hardening steels, such as the 7 per cent. manganese steel, and of normal carbon steel which has been hardened by sudden cooling. It is stable between the Ar. 2 and Ar. 3 points.

γ **iron** is also of the non-magnetic variety, and probably very hard, but ductile; it is characteristic of the 25 per cent. nickel and 12 per cent. manganese steels, and is stable only below the Ar. 3 point.

Graphite is a component of grey cast iron, being present in very thin flakes or laminated plates in the proportion of from 2·5 to 3·5 per cent. When such cast iron is fractured the "break" occurs through the skeleton graphite plates; and the fracture therefore appears to be almost entirely graphitic.

Slag.—This impurity of furnace origin is practically only found in the case of wrought iron, to the extent of about 0·2 to 2·0 per cent., as silicate of iron. It gives the "grain" effect in the rolling process, and can be readily detected as irregular dark blotches or patches in microscopic analyses.

The relative hardnesses of the constituents of carbon steels and irons has been investigated by Boynton,* who gives the values in Table XLV. on p. 265.

The tensile strength of pearlite itself has been shown by Professor Dalby to be about 62 tons per square inch, and it has also been found that the tensile strength of a pearlitic steel is proportional to the sum of the pearlite tensile strength and the ferrite or iron tensile strength.

* *Journal Iron and Steel Institute*, 1906, p. 287.

hardened air-hardening steel, and Fig. 136 shows the chief characteristics of this type of structure.

(*e*) **Austenite** is another constituent of steel, obtained when carbon steel containing more than 1·10 per cent. of carbon is heated above 1000° C. and quenched at about 0° C. It is softer than martensite, and can be scratched with an ordinary sewing-needle; it usually occurs as a mixture with martensite or hardenite.

The amount of austenite increases with the amount of carbon from nothing at 1·1 per cent. carbon up to about 70 per

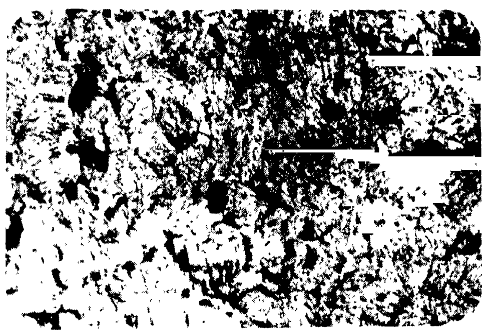


FIG. 137.—QUENCHED CARBON STEEL, SHOWING BACKGROUND OF SOLID SOLUTION WITH COMMENCEMENT OF DECOMPOSITION SHOWN BY THE BLACK PATCHES OF TROOSITE. × 400.

cent. at from 1·6 to 1·8 per cent. carbon; beyond this point it produces a separation of cementite, and therefore no longer increases.

(*f*) **Troosite** is obtained by quenching steels during the critical interval* or transformation period. It occurs as a slightly granular, almost amorphous, and mammillated structure, and in quenched steel (from the critical interval), it replaces the ferrite, and is surrounded by another constituent known as *Sorbite.*

Fig. 137 shows the structure of a quenched high-carbon steel, showing the background of solid solution, with commencement of decomposition shown by the presence of troosite (black).

* $Ar_{1 \cdot 2 \cdot 3}$.

in the internal condition of the metal occur at certain definite temperatures, corresponding to allotropic, isomeric, or solution changes, which are evident as heat absorptions or "arrests" on the temperature-time curve.

There are two types of changes which occur in the structure when the temperature varies at an uniform rate—namely, continuous and critical changes; the latter correspond to a sudden modification in the normal condition between a certain property and temperature. On heating and cooling temperature-time curves such changes are represented by discontinuity or the intersection of two branches of the curve.

The temperature scale is divided into a number of intervals by these critical changes, each interval corresponding to some internal change in the constituents; each metal must experience at least two such changes—namely, those corresponding to fusion and volatilization, but in many instances, such as in the cases of iron, steel, and non-ferrous alloys, other intermediate points of transformation occur.

These thermal changes are valuable indications of the micrographic structural arrangements.

Pure Iron Curves.

When practically pure iron is left to cool from the molten state, and the temperatures are plotted as ordinates at equal intervals of time—say, every ten seconds—the cooling curve obtained will be found to resemble that shown in Fig. 138.* It will be seen that there is one critical point at about 1530° C. corresponding to solidification.

The first "arrest," known as the Ar. 3 point,† occurs at about 860° C., and represents an allotropic transformation, whilst the Ar. 2 point, which occurs at about 750° C., marks another allotropic transformation or change in the material, accompanied by a change, with further cooling, from the non-magnetic to the magnetic condition; at each of the arrest points evolutions of heat occur, which correspond to a yielding

* Osmond, "The Microscopic Analysis of Metals."

† This notation is due to Osmond.

up of energy. The next arrest, known as the Ar.'1 point, occurs at about 690° C.

The above example is somewhat analogous to the case of water solidifying into ice, and yielding up its latent heat of "fusion" in the process.

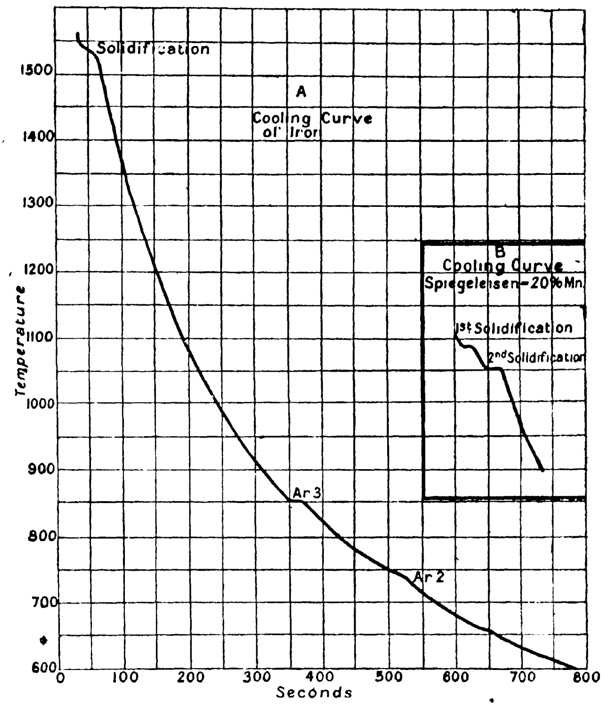


FIG. 138.—COOLING CURVE OF PURE IRON.

The three arrest points Ar. 3, Ar. 2, and Ar. 1, are also clearly evident in the case of carbon steels containing less than 0·35 per cent. of carbon.

The effect of the presence of any impurities, even in a very small quantity, is to lower (and often to smooth out) the arrest points; for example, these points are invariably lower for iron containing carbon than for pure iron.

Bodies which are mixtures of several constituents will have several solidification points, each corresponding, as a rule, to one of the constituents. The inset diagram in Fig. 138 shows the two solidification points for spiegeleisen,* which is an iron containing about 20 per cent. of manganese, at 1085° C. and 1050° C. respectively.

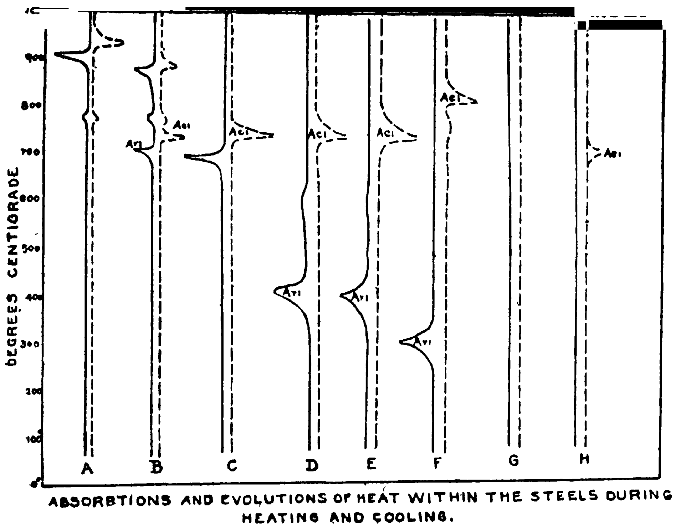


FIG. 139.—HEATING AND COOLING CURVES FOR STEELS

- - - - - Heating Curves —— Cooling Curves

A, Pure iron. D, High tensile steel G, 25 per cent nickel steel
B, Case-hardening steel E, Air-hardening steel H, Manganese steel.
C, Carbon steel F, Stainless steel.

When iron is slowly heated right up to its fusion point, absorptions instead of evolutions of heat occur at the critical points; the latter, however, occur at rather higher temperatures (usually from about 40° to 60° higher) than the arrest points obtained by cooling. Fig. 139† shows the heating and cooling curves for the different iron and steels indicated, the full lines corresponding to the cooling, and the dotted lines to the heating, curves.

* See also Appendix I. "Ferrous and Other Alloys."

† From Dr. Hatfield's "Steels used in Aero Work," *Aeron. Journ.*, 1917

In the example shown in curve *B*, Fig. 139, for case-hardening carbon steel, when the temperature is a little over 700° C., the pearlite constituent is changed into a homogeneous substance, which is a solid solution of iron carbide. This critical change is accompanied by an absorption of heat which is evident upon the temperature curve *B*, as an arrest point, and which is not shown upon the pure iron curve *A*.

The magnetic change point still occurs at the same temperature—namely, at about 770° C.—but the allotropic change point, *A.C.* 3, occurs at a much lower temperature.

In the case of the 0·6 per cent. carbon steel, the temperature curves (*C*, Fig. 139) show that the upper critical points have been lowered, and are apparently joined up with the carbon change points at about 730° C.

In this steel the major portion—namely, two-thirds—consists of the constituent pearlite, and hence it would be expected that the corresponding critical points to those of pure iron would be lowered (in temperature) and would be more marked; curve *C* shows that this is the case.

The heat absorption, corresponding to solution during heating, occurs at 730° C., whilst the evolution of heat during cooling, which is associated with the solidifying of the ferric carbide solution, takes place at about 700° C.

Referring to curve *G*, Fig. 139, it will be seen that no critical points occur during cooling, or heating, over the usual range of working temperatures; it is for this reason that the 25 per cent. nickel steel alloy is non-magnetic, its condition corresponding with the solid solution state.

Similarly, in the case of 12 to 14 per cent. manganese steel, if heated up from the untempered state, and cooled sufficiently quickly, it retains the "solid" state and shows no critical points. In the tempered state an arrest point is, however, evident, as shown in curve *H*, Fig. 139, in the neighbourhood of the carbon change point; the cooling curve will not, of course, reveal any corresponding critical point. When this type of steel is cooled sufficiently rapidly it is found to be non-magnetic.

Solidification Curves for Alloys and Carbon and Iron—Eutectics.

It has already been stated that metals under varying temperature conditions behave in a somewhat similar manner to liquid solutions; this resemblance will here be considered more fully.

When a solution of salt and water is progressively lowered in temperature it will be found to begin to freeze at a lower temperature than that of water alone. If a number of such

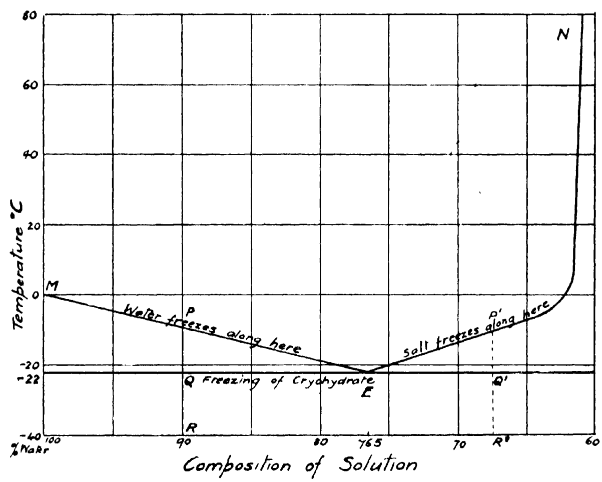


FIG. 140.—SALT SOLUTION CURVES.

solutions containing different proportions of salt and water be taken, and their initial freezing-points be plotted against their percentage compositions, curves similar to *ME* and *EN* (Fig. 140) will be obtained.

Consider any solution, such as represented by *PQR*, containing 90 per cent. of water and 10 per cent. salt, when the temperature reaches the value denoted by *P*—namely, $-9°$ C.—the solution begins to freeze, and in consequence of the ice separating out first the remaining liquor becomes richer in salt, thereby causing a lowering of its freezing-point

along the line PE, ice separating out the whole time, until at $-22°$ C., the "mother-liquor" remaining, which consists of about 23·5 per cent. of salt, freezes bodily. Similarly, if a solution containing more than 23·5 per cent. of salt, as represented by the point P^1 be cooled, salt will separate out when its temperature reaches the value represented by P^1, and will continue to separate out along NE, causing the remaining liquor to become progressively weaker in salt, until, as before, at $-22·5°$ C. the remaining solution will solidify bodily without further separation.

Similar phenomena occur in the case of alloys when cooled from the fusion point.

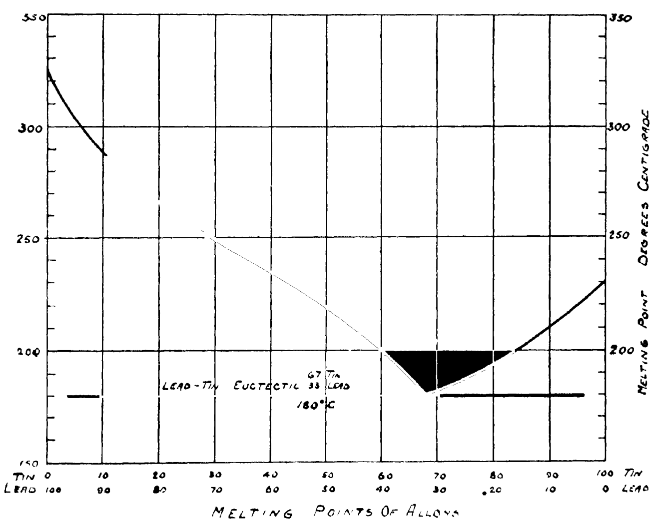


FIG. 141.—COOLING CURVES FOR LEAD-TIN ALLOYS

Lead-Tin Alloys.

Fig. 141* represents the freezing-point curves of lead-tin alloys similar to bearing metals; this is a simple example, as most alloys are more complex in their behaviour.

In the first place, it will be seen that the solidifying-points of

* From Cantor Lectures on "Alloys," 1897, Professor W. C. Roberts Austen.

all the alloys are lower than that of pure lead (326° C.). Next, consider any alloy richer in lead—say, one containing 70 per cent. lead and 30 per cent. tin; it will begin to solidify at 250° C., and lead will be deposited, the remaining mixture becoming richer in tin, thereby lowering its solidifying-point until, when the temperature reaches 180° C., the composition consists of about 69 per cent. tin and 31 per cent. lead, and the whole solidifies without further selective separation. This mixture, which corresponds to the mother-liquor of the salt solution previously described, is called the lead tin *eutectic*. An *eutectic* is usually defined as the most fusible alloy of two or more metals;* that is to say, it has the lowest fusion or melting point of any of the mixtures of the metals.

Copper-Zinc Alloys.

Many alloys, such, for example, as copper and zinc, consist of metals which are not solvents in each other, but which act as solvents for chemical compounds of the constituent metals.

For example, near the melting-point of copper large amounts of zinc will combine with the copper to form a zinc-copper compound, which will in its turn dissolve in the free copper. For each given mixture of copper and zinc there is one fixed temperature at which the solid solvent is in equilibrium with the liquid part. At this point any further slight lowering of temperature will cause solidification of the whole mass, whilst any heat addition will cause liquefaction. When the temperature is progressively lowered the copper crystallizes out, until at 890° C. the alloy solidifies bodily. The remaining metal consists of an eutectic of copper and a copper-zinc compound, and is analogous to the "mother-liquor" of a salt solution. It will be seen that this is not the same simple effect occurring in the lead-tin series.

Many alloys, when fluid, consist of several solutions, each of which, upon cooling, leaves a solid deposit and a liquid mother-liquor. These mother-liquors do not, however, combine, and there may therefore be several eutectics; in the case

* Guthrie, *Phil. Mag.*, vol. xvii., p. 462.

of copper-zinc alloys there are at least four eutectic alloys, whilst for copper-tin there has been shown to be six, at least.

Fig. 142 shows the solidifying-point curves for copper-zinc alloys (or brasses). It will be observed that there are four horizontal branches *b*, *c*, *d*, and *e*, each indicating the presence of eutectic alloys.

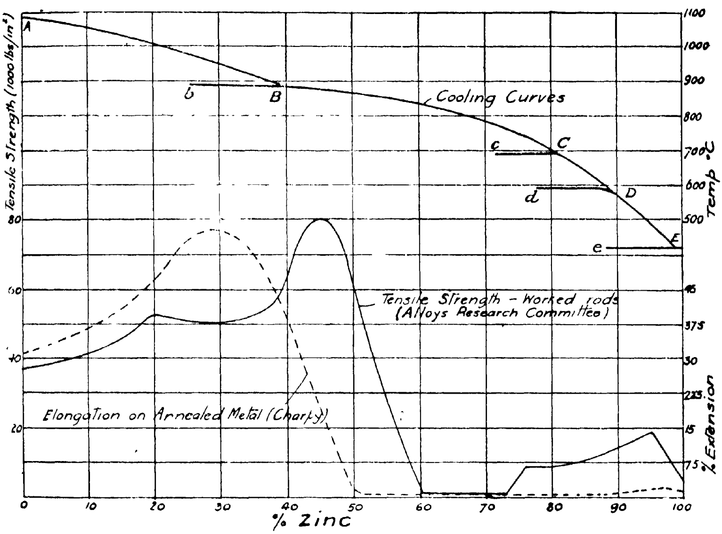


FIG. 142.—COOLING AND STRENGTH PROPERTY CURVES FOR COPPER-ZINC ALLOYS OR BRASSES.

Steels.

Fig. 143* shows the solidification, or equilibrium, curves for iron and carbon, the carbon varying from nothing up to 1·6 per cent.; the ordinates corresponding to each proportion of carbon represent the temperatures at which, upon cooling, from the molten state, evolutions of heat occur.

It has been known for a long time that iron can exist in more than one allotropic† form, and the branches A_3B and

* Osmond.

† When a metal or element having a definite chemical composition can exist in several forms, having different physical properties but the same chemical composition, these are known as "allotropic" forms.

A_2B correspond to the allotropic transformations of iron. These two branches unite at B in a single branch BE, when more than 0·2 per cent. of carbon is present.

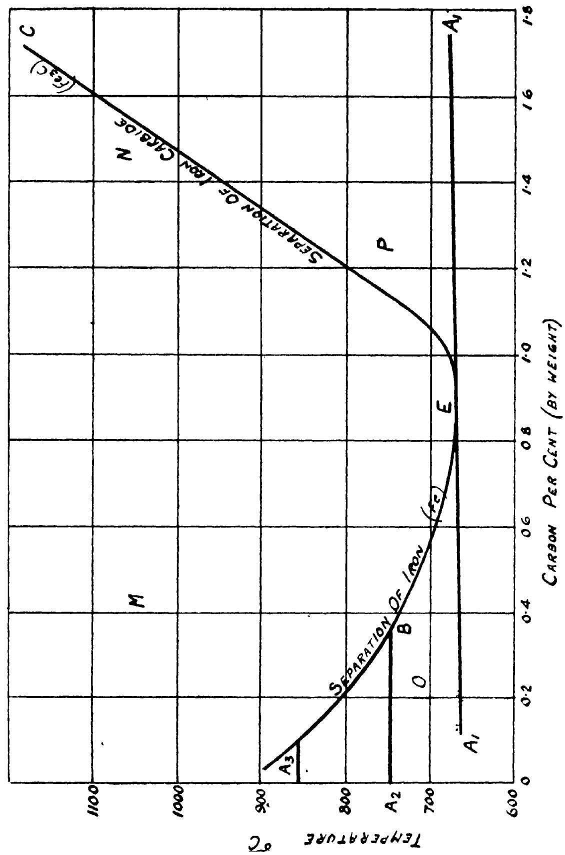


Fig 143.—Equilibrium Curves for Iron-Carbon

Along the branch A_3BE, the solution of iron and carbide of ron, upon further cooling, begins to deposit ferrite, until, when the temperature of about 670° C. is reached, corresponding to about 0·9 per cent. of carbon, the remaining eutectic, consisting of *ferrite* and *cementite* (or carbide of iron), solidifies out in the form of *pearlite*.

At the point E a sudden evolution of heat, distinguishable by eye, occurs, accompanied by a temporary expansion; this phenomenon is known as "recalescence."

The branch BE of the curve, then, corresponds to a separation of *ferrite*, and the branch EC to one of carbide of iron (Fe_3C), or *cementite*, whilst the nearly horizontal branch A_1EA_1 represents alternating layers of these two constituents, which have already* been shown to constitute *pearlite*, and which corresponds to a definite composition. This line A_1EA_1 corresponds to the temperature above which the steel begins to harden by quenching.

The branch BE represents the equilibrium curves of slowly cooled iron and steel, consisting of less than 0·9 per cent. carbon, and corresponds to mixtures of *ferrite* and *pearlite* in proportions depending upon the initial carbon content. Steels with 0·9 per cent. of carbon consist of pure *pearlite*, whilst those of higher carbon content contain both *pearlite* and *cementite*.

Effect of Quenching Steels.

If, instead of allowing the molten steel to cool slowly, it is allowed to cool to a certain temperature and then is quenched in a cold liquid, the above actions become altered, for they have not had time to be completed in the reduced temperature interval.

The carbon in such steels partially retains the dissolved carbon state corresponding to the higher temperatures—namely, the "hardening carbon." If the quenching in the case of a lower carbon content steel than 0·9, such as that which is represented by the point M in Fig. 143, occurs from a point above the curve BE, then the resulting constituent does not contain either *ferrite*, *pearlite*, or *cementite*, but the needle-like structure known as *martensite*,† which corresponds to maximum hardness for the given steel.

As the percentage of carbon in the steel increases the needles of *martensite* become smaller and less distinct, but the hardness increases.

* See p. 253. † See Fig. 261.

Above 0·9 per cent. of carbon, the effect of quenching from a point such as N, on the side EC of the curve (Fig. 143) is to cause the structure to consist of two constituents—namely, *austenite* (which is readily scratchable with a needle) and *hardenite*.

If lower carbon steel be quenched from a temperature below BE, but above A^1E, the constituents of the chilled metal consist of the isolated white *ferrite*, separated out below BE, and striated *martensite*. Steel containing more than 0·9 per cent. carbon, if quenched from a temperature such as P (735° C.) below EC, but above EA^1, will contain both the *cementite*, which has separated out below EC prior to quenching, and *martensite*.

It will be seen from the examples given that the thermal phenomena are associated with, and often afford valuable information upon, the subject of the microscopical constitution of metals; indeed, the hardening and tempering effects are readily explained in this manner.

Equilibrium Diagram for Iron and Carbon.

The diagram shown in Fig. 144 is obtained by plotting, as temperature ordinates, the arrest points of a very large number of iron-carbon alloys, varying in constitution from pure iron (C=0·00 per cent.) up to cast iron (C=5·00 per cent.), through the range of carbon steels. It should be emphasized that the curves of equilibrium shown correspond with the arrests upon the cooling curves of these materials. One or two of the lines upon the diagram, however, have been obtained or confirmed by indirect methods.

The line AB shows that as the proportion of carbon increases from nothing to about 4·3 per cent., the melting-point falls from about 1500° C. for pure iron at A down to 1140° C. for the eutectic, or pure pig iron at B. The fusibility of cast irons is evident from this fact.

The line EGH shows the effect of the single constituent solid solution in lowering the temperature of the metal until it contains 0·9 per cent. of carbon; the lines EG, GH, and HD correspond to the lines A_3B, BE, and EC in Fig. 144.

Below 700° C. the solid solution solidifies into pearlite or

cementite, as indicated by the horizontal line LHJ, at practically the same temperature over the whole carbon range. If any vertical line, such as XY, be drawn upon the diagram, the manner in which it cuts the equilibrium curve will determine the constitution of the corresponding carbon content steel; for example, in the case of XY, which corresponds to 0·6 per cent. of carbon, it will be seen that solidification commences at

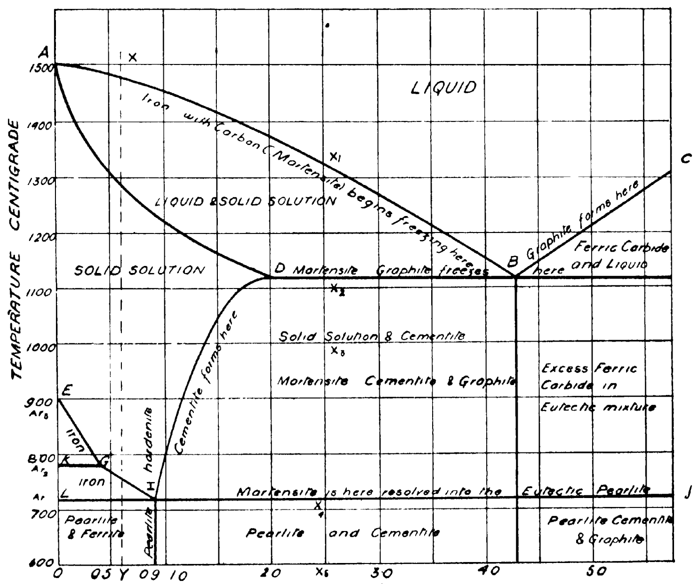


FIG. 144.—EQUILIBRIUM CURVES FOR IRON AND CARBON.

about 1460° C., and is followed by complete solidification where XY cuts AD. This mass then cools down until it reaches the point where XY cuts GH—that is, to a temperature of about 730° C.—when a small amount of γ and α allotropic forms of iron separate out.

At about 20° to 30° lower temperature, when the line LHJ is reached, pearlite separates out, and the whole mass becomes a solid steel, containing a large proportion of pearlite, in which small ferrite areas occur.

With a lower carbon content, greater ferrite areas will occur.

The effect of rapid cooling from the solid solution region will be to retain in the solid metal much austenite.

Similarly, the constitution of any other carbon content steel or cast iron may be examined by means of the given equilibrium curves.

High-Carbon Metal.

Consider the case of iron with 2·5 per cent. of carbon cooling from the molten state; this combination approaches the limits of cast iron, since it only requires about 2 per cent. of carbon to saturate solid γ iron; the martensite, which continues to solidify from about 1280° C., rejects all carbon in excess of this quantity, and leaves it in the remaining molten mother-liquor.

This process continues from the point X_1 to X_2 (Fig. 144)—that is, until a temperature of about 1125° C. is reached, when the carbon content of the mother-liquor reaches about 4·3 per cent.; as further cooling occurs below the line AB the mother-liquor solidifies bodily into an eutectic mass of graphite and martensite.

When the temperature of 1000° C. is reached at X_3 part of the graphite unites with some of the iron, to form cementite, and the mixture between X_2 and X_3 therefore consists of martensite, cementite, and graphite. At X_4 this martensite, which has now become hardenite, splits up into pearlite, so that the resulting metal contains pearlite, cementite, and graphite, after cooling down to the completely solid state.

Alloy Steels.

The presence of elements in steel, such as *nickel*, *chromium*, *tungsten*, and similar elements, tends to alter the solidifying and critical points in exactly the same manner that the presence of carbon does.

The critical points are lowered by both *nickel* and *manganese*, as the curves given in Fig. 139 clearly show. Thus, with 25 per cent. of nickel, or 12 per cent. of manganese, the Ar. 3 point is lower than the usual 20° C.; such steels are characterized by the presence of martensite similar to rapidly cooled

carbon steels, and normally consist of γ iron modified by the large amount of manganese or nickel with which it is alloyed.

It should be mentioned here, that in carbide of iron (Fe_3C) the iron is capable of being partially replaced by other elements, such as those present in alloy steels.

The two special nickel and manganese alloy steels above mentioned are practically non-magnetic.

Referring to Fig. 139 again, it will be seen that in the case of *nickel-chrome steel* (curves D and E) the change to the solid solution state, with heat absorption, occurs at about the same temperature during heating as in the case of the carbon steels, but the *arrest points* occur at an appreciably lower temperature during cooling. For this reason the effect of the elements nickel and chromium is to make the carbon change more sluggish—that is to say, more easily controlled and suppressed, so that larger masses of this alloy steel can be satisfactorily heat treated and hardened.

In the case of *air-hardening steels*, the speed of cooling which results from the air-hardening process is sufficiently rapid to suppress the carbon change, and to cause the mass to retain its solid solution state.

Figs. 135 and 145* show the structures of this type of steel in the hardened states respectively.

The alloy steels are easier to obtain the "solid solution" state with, and this usually occurs with heat evolution during cooling at a lower temperature. It should be pointed out that if the thermal change point can be suppressed by quenching, rapid cooling, or otherwise, the breakdown from the solid solution to the pearlitic condition is prevented.

In the case of *manganese steel*,† when the percentage of manganese lies between about 12 and 14, the cooling curve, from the molten state, shows no "arrest," and the solid solution state can be readily preserved by a sufficiently rapid cooling. Thus, if this high manganese steel be quenched at about 950° C. a non-magnetic and tough condition results (Fig. 146).

* Dr. Hatfield. † Discovered by Sir R. A. Hadfield.

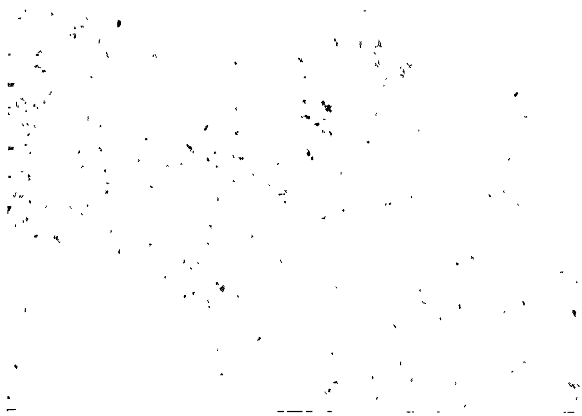


FIG. 145.—ANNEALED AIR-HARDENING STEEL. ETCHED. × 500.

FIG. 146.—MANGANESE STEEL. MICRO. ETCHED. × 100.

High *nickel steel,* containing about 25 per cent. of nickel, is also non-magnetic, for no absorptions or arrests of heat occur during heating or cooling the ordinary range of working tem-

peratures met with commercially, so that the solid solution state, modified only by the high percentage of nickel present, is obtained.

The micro-structure of this steel, in its best condition, consists of polygonal grains or allotromorphic crystals of solid solution of carbide of iron and nickel, in iron containing nickel.

In *air-hardening nickel-chrome steels* the effect of the particular proportions of nickel and chromium is to render the speed

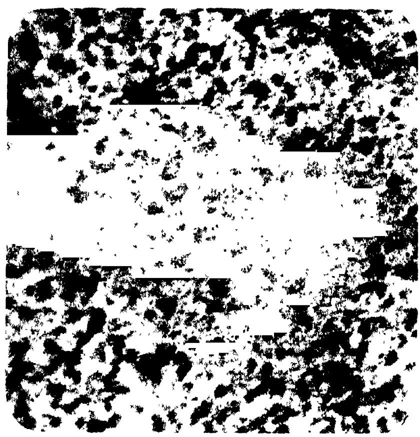


FIG. 147.—MAGNET STEEL (TUNGSTEN). ETCHED. × 500.

of cooling quick enough to suppress the carbon change point and to present the solid solution state, in which the material at ordinary temperatures is extraordinarily hard and tough.*

The Time Factor.

It has been shown by Professor Edwards† that much of the diversity of opinion about the exact effect of chromium upon steel has been due to the omission to take account of the rate of cooling, or the time-factor effect, when studying the results of investigations. He has shown, for example, that in the case

* Tensile strengths up to 125 tons per square inch, and hardnesses (Brinell) up to 550 are obtained with these steels.

† See footnote, p. 284.

of a chrome steel containing a little over 6 per cent. of chromium and 0·63 per cent. of carbon, that when specimens were heated to 1000° C. and allowed to cool, (*a*) in still air, on an asbestos pad, taking thirty minutes to reach atmospheric temperature, and (*b*) in the furnace, taking sixty minutes to reach ordinary temperatures, that in Case (*a*), the Brinell hardness was 642, whereas in Case (*b*) the hardness was only 281. Thus the steel became what is known as "self-hardening" in the one case, and "soft" in the other, due to the different rates of cooling.

Table XLVI. shows the influence of the time factor upon the hardness of the above-mentioned chrome steel when cooled from an initial temperature of 1200° C. In connexion with these results, it was observed that with the slower rates of cooling the critical temperatures were higher, but the rises of temperature, or heat evolutions, were much greater; as the cooling rate increased, so the critical points became lower and less marked, until, with a rate of about two minutes, there was no noticeable carbon change point, and maximum hardness (Brinell 680) occurred. The more rapid cooling rates cause the carbon change points to be entirely suppressed, and micro-photographs of chrome steels cooled at different rates show that the constitution, as the rate of cooling is increased, corresponds to increasing percentages of solid solution carbon—that is to say, to greater proportions of austenite, martensite, or hardenite.

TABLE XLVI.

Effect of Cooling Rate upon Hardness of Chrome Steel.

[Composition: Carbon, 0·63 per cent.; chromium, 6·18 per cent.]

Initial Temperature, 1200° C

Cooling rate in minutes	*min.*	*sec.*	*min.*	*sec.*	*min.*	*sec.*	*min.*	*sec.*	*min.*	*sec.*	*min.*	*sec.*	*min.*	*sec.*
	19	8	16	28	12	33	12	8	8	51	3	33	2	2
Brinell Hardness	333		337		398		503		632		664		680	

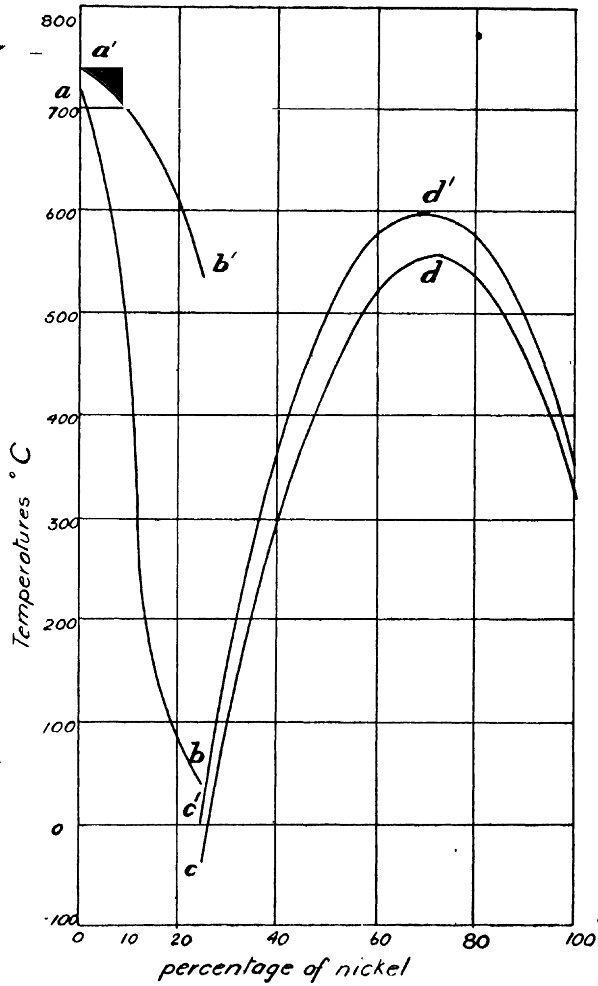


FIG. 148.—HEATING AND COOLING CURVES FOR NICKEL STEEL.

Metallography of Nickel Steels.

When nickel is present in carbon steel its effect, apart from strength considerations, which will be considered later, is to lower the critical temperatures; the higher the percentage of

nickel, up to about 25 per cent., the lower the arrest point, until, with this latter proportion, there is no definite critical point at temperatures down to 20° C. when the metal is cooled down slowly.

Fig. 148 shows the critical temperatures for low-carbon nickel-steel with different proportions of nickel. The upper curve a^1b^1 corresponds to the slow heating curve, and ab to the slow cooling curve. It will be seen that during cooling, with increasing nickel content up to 27 per cent., the critical

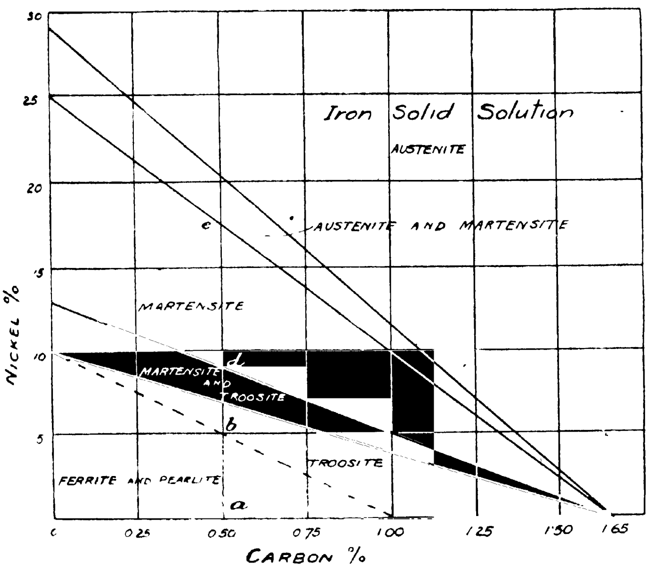


FIG. 149.—EQUILIBRIUM CURVES FOR NICKEL-CARBON.

temperature of sudden heat evolution becomes progressively lower, until, with 25 per cent. of nickel, it occurs at atmospheric temperatures.* This metal is therefore non-magnetic at atmospheric temperatures.

If, however, this nickel steel is cooled below 0° C. the mag-

* Also *vide* "The Hardening and Tempering of Steel," by Professor Q. A. Edwards.

netic transformation occurs, and if the temperature is raised the magnetic state persists right up to above 500° C., as shown by the critical point b^1. Similarly, for lower content nickel steels when heating occurs the critical temperatures are much higher, as shown by the curve a^1b^1. Hence, for this range of nickel steels the magnetic, or non-magnetic state occurs according to whether the temperatures within the area abb^1 are approached by heating or cooling, and this group of steels is termed an "irreversible" one. The microscopic structure of nickel steels with different proportions of nickel (up to 30 per cent.) and of carbon (up to 1·65 per cent.) has been found by Dr. Guillet* to correspond to the equilibrium diagram shown in Fig. 149.

It will be seen that low carbon content steels contain more ferrite and pearlite, and that high carbon contents have a constitution of both troosite and martensite, with some austenite.

Flow Structure of Steel.

It is frequently of importance, in connexion with the stamping, pressing, forging, and general plastic treatment of steel, to be able to examine the lines of flow, or grain, of the metal. One of the commonest methods employed for this purpose is that of sulphur printing, which utilizes the effect of the small quantities of sulphur present upon silver bromide printing paper. In Baumann's method the surface to be examined is machined flat and polished with emery paper No. 1. The silver bromide paper is soaked in very dilute sulphuric acid (about 1 to 3 per cent.) solution in water, and is placed on the metal surface; the acid attacks the sulphides and liberates hydrogen sulphide, which acts upon and turns the silver bromide dark in colour. The auto-print is removed from the metal, washed, and then immersed in sodium hyposulphite to fix (or remove the excess bromide). The average period of time required is about one to two minutes.

Fig. 150† shows a typical sulphur print made from a section

* *Engineering*, March 8, 1918.

† Courtesy of "The Institution of Automobile Engineers."

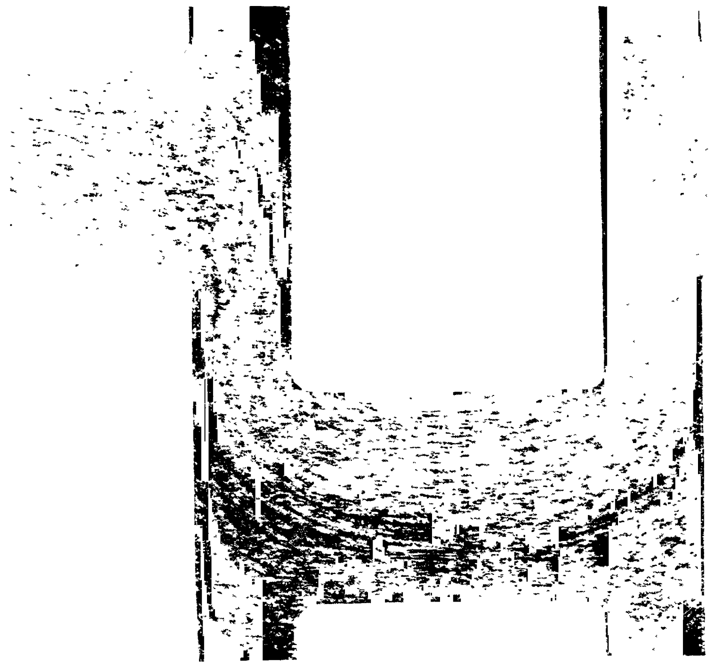


FIG. 150.—SULPHUR PRINT FROM FORGED AND STAMPED CRANK-SHAFT.

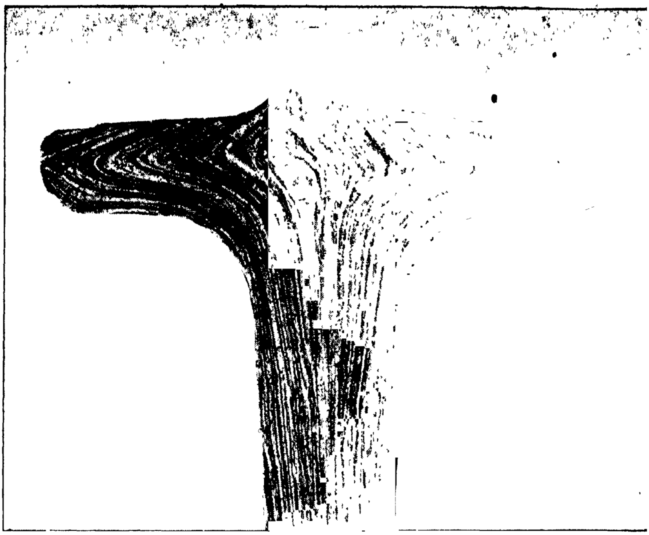


FIG. 151.—VALVE STAMPING, SHOWING SATISFACTORY FLOW OF METAL.

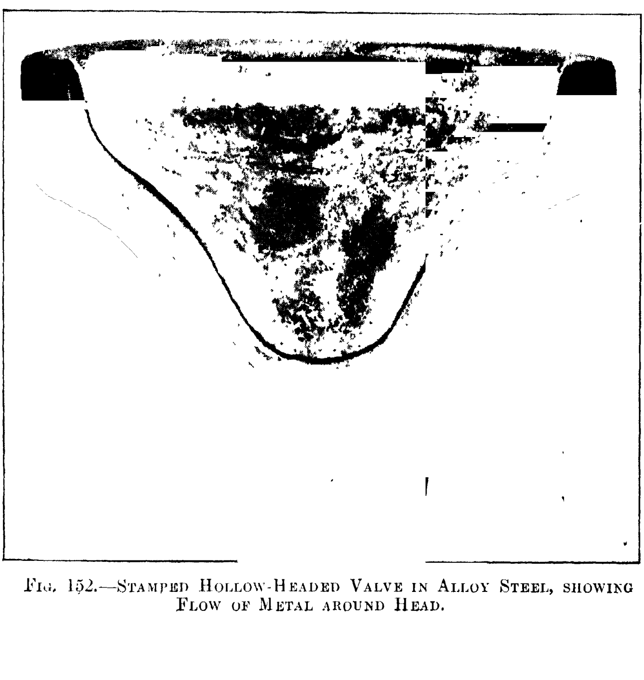


FIG. 152.—STAMPED HOLLOW-HEADED VALVE IN ALLOY STEEL, SHOWING FLOW OF METAL AROUND HEAD.

of a forged and stamped automobile engine crank-shaft; that the method of manufacture is satisfactory is shown by the flow of the grain.

Another method often employed consists in polishing the surface thoroughly and etching with a 10 to 20 per cent. nitric acid solution.

Figs. 151, 152, and 153 show the flow structure of stamped and turned alloy steel valves for aeroplane engines; the differ-

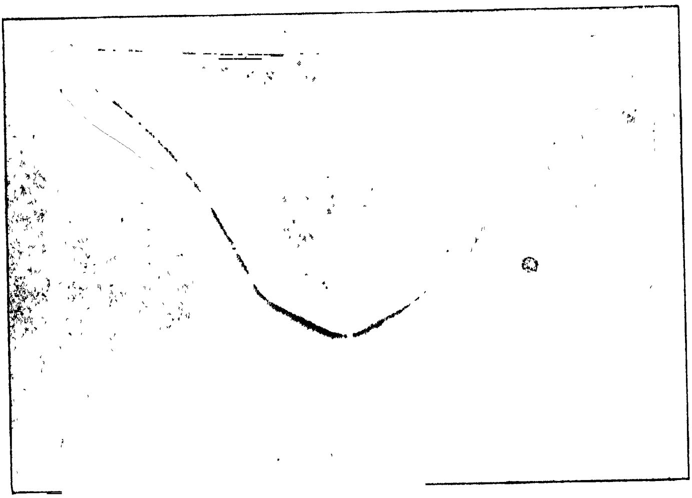


FIG. 153.—VALVE TURNED FROM SOLID-DRAWN BAR (UNSATISFACTORY FLOW STRUCTURE).

ence between the stamped valves in Figs. 151 and 152 and the solid bar turned valve in Fig. 153 is marked.

Heat tinting is another method employed, which depends upon the colours of the oxides of the iron and the phosphorus content.

If polished sections are heated to a certain temperature the phosphorus-rich portions appear as yellowish white streaks, and the purer metal as a blue background.*

* For fuller particulars *vide* "The Microscopic Analysis of Metals," by Osmond and Stead.

CHAPTER V

IRONS AND CARBON STEELS

Physical and Mechanical Properties of Ferrous Metals.

It is not proposed in the present work to consider the modes of extraction of metals from their ores or the metallurgical processes employed in the derivation of the various final forms of ferrous metals, except, perhaps, in so far as they enter into questions of heat treatment but to confine these considerations to the properties of the final products, commencing with the more elementary irons and steels, and leading up to the more complicated alloy steels.

Iron.

There are three principal forms of iron occurring in commercial work—namely, (1) Wrought Iron, (2) Cast Iron, and (3) Malleable Iron, which will be dealt with in the order named.

1. Wrought Iron.

This metal is not employed for stress members in aircraft or automobile work, but only for certain electrical parts, such as the pole pieces of electro-magnets, cores, armature plates, and similar purposes; its physical properties are, however, of interest in relation to those of the more modern steels.

Wrought iron is manufactured from cast iron by the process of puddling, forging, and rolling, after which treatment only a very small percentage of carbon remains, usually from 0·05 to 0·15 per cent.

Certain impurities, such as manganese,* silicon, sulphur, and phosphorus, are usually found in the resulting metal, and its physical properties are affected thereby. For example, the effect of more than about 0·1 per cent. of phosphorus in

* Manganese (0·5 per cent.) also tends to make iron "cold short."

iron is to make the metal "*cold short*"*—that is, to cause it to crack if bent cold, although it may be readily bent hot. Sulphur, when present in more than 0·1 per cent., causes "*red shortness*," or failure during forging or hot working.

Wrought iron, which should contain not less than 99 per cent. of iron, is a silvery metal, which is soft and ductile, the degree of ductility depending upon its purity. The metal as rolled and forged has a fibrous structure, which is caused by the presence of slag in the original ingots; iron bars and plates invariably show an appreciable difference in mechanical properties along and across the direction of rolling, and the presence of slag particles can be readily detected by microscopic examination. The metal softens at a temperature of from 800° to 900° C., and can be readily welded in this condition.

Commercial wrought is divided into grades, known as (*a*) Merchant Bar, (*b*) Best Iron, (*c*) Double Best, and (*d*) Treble Best. Best iron is superior to merchant bar, and is made by cutting up the latter into short bars, faggoting, and re-rolling; the better grades receive a repeated similar treatment. The best qualities of iron are the charcoal, electrolytic, and Swedish irons; these, in the annealed condition, are used for electrical purposes, and in the production of high tensile steels.

Typical Chemical Composition.—The following is a typical composition of wrought iron, the figures denoting percentages.

Carbon [0·02 to 0·2], Manganese [0·00 to 0·3], Silicon [0·00 to 0·2], Sulphur [0·00 to 0·015], Phosphorus [0·00 to 0·15], Iron [99 to 99·5].

Mechanical Properties.—The tensile strength of good wrought iron varies from about 22 to 25 tons per square inch, with an elongation of from 20 to 25 per cent., and a reduction of area of from 50 to 60 per cent.

Tensile strengths as low as 16 and as high as 28 tons per square inch have been met with in commercial work, but the above represent typical values.

* Silicon makes iron hard and brittle if more than 0·1 per cent. is present.

The tensile strength of strips taken from rolled plates in the direction of rolling usually ranges from 20 to 25 tons per square inch, whilst for strips taken across this direction it is appreciably lower—namely, from 16 to 22 tons per square inch, the reduction of area varying in this case from 75 to 85 per cent.

Wrought iron shows a well-marked yield point of from 15 to 17 tons per square inch; its elongation is about $\frac{1}{1000}$ of its length for each ton per square inch within the elastic limit, which varies from 14 to 16 tons per square inch for good qualities of this iron.

The crushing strength of wrought iron is rather indefinite, but may be taken at 0·8 of its tensile strength.

The shearing strength varies from 15 to 20 tons per square inch, and is less when sheared along the direction of rolling (or parallel to the slag grain).

The Modulus of Elasticity for wrought iron varies from 12,000 to 13,000 tons per square inch, being about 12,500 upon the average.

The Modulus of Rigidity is about 5000 tons per square inch.

Physical Properties.—The effects of temperature upon the tenacity and the allotropic modifications have already been referred to.*

Microscopic examination of the structure of wrought iron reveals the ferritic structure, as shown in Figs. 123 and 154, characteristic of low-carbon steels slowly cooled, interspersed with slag particles. The direction of rolling, bending, or working, can also be readily detected.

The specific gravity of wrought iron varies from 7·8 to 7·9; a cubic foot of wrought iron of specific gravity 7·78 weighs 486 lb., and a cubic inch, 0·280 lb. Cast iron has a lower specific gravity, varying from 7·0 to 7·5, according to its composition.

The melting-point of pure iron is about 1530° C.

The coefficient of linear expansion of wrought iron is $10{\cdot}2 \times 10^{-6}$ and of cast iron $11{\cdot}9 \times 10^{-6}$.

The thermal conductivity of pure iron at 18° C. is 0·161, and

* *Vide* pp. 98 and 264 *et seq.*

at 100° C. 0·151, in *C.G.S.* units; the corresponding values for wrought iron are 0·144 and 0·143 respectively. Cast iron at 100° C. has a conductivity of 0·111, and 1 per cent. steel 0·107.

The specific heat of iron from 20° to 100° C. is 0·119,* and from 0 to 1100° C. it is 0·153.†

The electrical resistivity of pure and wrought irons at 18° C. are 9 to 15×10^{-6} and $13{\cdot}9 \times 10^{-6}$ ohms per sq. cm. respectively; for 0·1 per cent. steel the value is $19{\cdot}9 \times 10^{-6}$.

The velocity of sound in wrought iron is 49 to 51 centimetres per second.

Electrolytic Iron.

A very much purer form of iron than that previously described can be produced by electrolytic means, and the manufacture of this type of iron is now a commercial proposition. The principle of the different processes consists in making the anode of wrought, cast iron, or carbon steel, and the electrolytic solution of one of the salts of iron, such as ferric chloride, ferric sulphate, or mixtures of such salts; where an electric current of sufficient density is employed, pure iron is deposited upon the iron cathode. The following description‡ refers to one of the typical processes—namely, that of the Le Fer Company at Grenoble: " In principle the method consists in the use of a revolving cathode and a neutral solution of iron salts maintained in the neutral state by the circulation of the liquid over the surface of the iron. The bath also receives periodic additions of a depolarizing medium, such as iron oxide, the object of which is to eliminate, at least in part, the hydrogen deposits upon the cathode, which injuriously affect the material if present in too large a quantity. By this means it is possible to work with a current of high density (1000 ampères per square metre), and an iron of excellent

* Schmitz. † Harker.

‡ "Electrolytic Iron: Its Manufacture, Properties, and Uses," by L. Guillet, Proc. of the Iron and Steel Institute; reproduced in *Engineering*, October 2, 1914.

quality is obtained. The process is applicable to the production of very pure iron, which can compete with 'best iron' or Swedish iron, or to the direct manufacture of tubes and sheets in the finished state."

The average composition of electrolytic iron, obtained by using any pig iron in solution, after annealing, is approximately as follows: Carbon [0·004], Silicon [0·007], Sulphur [0·006], Phosphorus [0·008], Iron [99·975], percentages.

With a current density of 1000 ampères per square metre, it is stated that a yield of 2 tons of metal is obtainable, per kilowatt-year, including the cost of current for the accessory services.

FIG. 154.—ELECTROLYTIC IRON (ANNEALED). ETCHED. × 300.

Properties.—The electrolytic iron in the deposited state is hard and brittle, showing under the microscope a characteristic grain resembling the fine needles of martensite.

Upon annealing from about 700° to 800° C. the well-known ferritic structure is obtained; the annealing process not only improves the strength qualities but also serves to eliminate the absorbed gases, such as the hydrogen, carbon-monoxide, oxygen, etc. Fig. 154 shows the ferritic structure of annealed electrolytic iron. The tensile strength of the annealed iron varies from 19 to 20·8 tons per square inch, with an elongation of from 40·2 to 42·1 per cent. in the direction of the length of the cathode.

The effect of compression tests* upon annealed tubes shows that a remarkable degree of deformation can be undergone without signs of fracture; thus, a tube of 100 mm. diameter, and of 0·75 mm. thickness, when subjected to a compression of 1200 pounds per square inch, underwent a permanent deformation of a regular character, as if squeezed in a press.

The Brinell hardness in the deposited state is about 193, for the 10 mm. ball and 3000 kg. load, whilst in the annealed state it is about 90.

Electrolytic iron corrodes easily; this is believed to be due to its content of iron chloride. It has a low hysteresis and a high permeability, which renders it very suitable for electrical work.

The electrical conductivity is given as 10·22 microhms per cub. cm. for the annealed iron at 20° C.

The critical points were found to be, for the deposited iron, 981° and 937° C. (heating), and 902° and 778° C. (cooling); whilst for the annealed iron they were 788° and 932° C. (heating), and 902° and 778° C. (cooling).

2. Cast Iron.

The product which is obtained directly from iron ores when suitably smelted in the blast furnace is known as pig iron, or cast iron.

Its composition depends upon that of the ores and smelting materials. and varies over an appreciable range. The principal constituents of cast iron are as follows:

Carbon, in the combined or graphic form ..	2·0 to 5·0 per cent.
Silicon	0·15 to 5·0 ,,
Phosphorus	0·0 to 1·3 ,,
Manganese	0·0 to 1·5 ,,
Sulphur	0·0 to 0·5 ,,
Iron	90·0 to 95·0 ,,

Definitions of Cast Irons.†

Pig Iron.—Cast iron which has been cast into pigs direct from the furnace.

* See Fig. 178.

† International Association of Testing Materials, Brussels, 1906.

Basic Pig Iron.—Pig iron containing only a small quantity of silicon and sulphur, so that it is easily convertible into steel by the basic open hearth process (the pig iron should contain not more than 1 per cent. of silicon).

Bessemer Pig Iron.—Pig iron containing only a small quantity of phosphorus and sulphur, so that it is easily convertible into steel by the original or acid Bessemer process (the pig iron should contain not more than 0·10 per cent. of phosphorus).

Alloy Cast Irons.—Irons, the properties of which depend upon the presence of some other element or elements than carbon.

Cast Iron.—Iron containing such a percentage of carbon that it is not malleable at any temperature; it is recommended to accept 2·20 per cent. carbon as the dividing-point between steel and cast iron.

Charcoal Hearth Cast Iron.—Cast iron which has had its silicon and phosphorus removed in the charcoal hearth but still retains enough carbon to be specified as cast iron.

Grey Cast Iron and Grey Pig Iron.—Cast and pig iron in the fracture of which the iron itself is nearly concealed by graphite, so that fracture has a graphitic colour.

White Cast Iron and White Pig Iron.—Cast iron and pig iron in the fracture of which little or no graphite is visible, the fracture being silvery and white.

Malleable Pig Iron.—Pig iron suitable for converting into malleable castings by the process of melting, treating when molten, casting in a brittle state, and then making malleable without remelting.

Refined Cast Iron.—Cast iron which has had most of its silicon removed in the refinery furnace but still retains sufficient carbon to be specified as cast iron.

There are three principal kinds of cast iron, known as the *Grey*, *Mottled*, and *White* varieties respectively.

Grey Cast Iron contains most of its carbon, not in the combined form, as in the case of the white varieties, but in the free or graphitic state, and is, consequently, much greyer.

and softer, weaker in mechanical properties, but more fusible than the white or mottled irons.

The following is a typical composition of a grey cast iron: Iron [90·38], Carbon (combined) [1·00], Carbon (graphitic) [2·66], Silicon [3·00], Sulphur [1·20], Phosphorus [0·90], Manganese [0·86].

The presence of aluminium and silicon in cast iron has the effect of hindering the combination of the carbon, and thus causes the separation of the graphite, so that irons containing much silicon are of the greyer varieties; the effect of the presence of this element will be considered more fully later.

FIG. 155.—GREY OR WEAK CAST IRON. ETCHED. × 50.

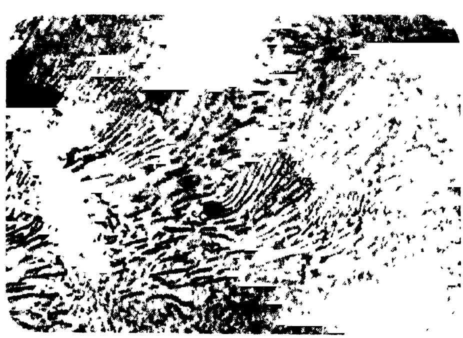
Microstructure of Cast Irons.*—The combined carbon in cast irons is present in the form of carbide of iron, or pearlite, and the greater the proportion of combined carbon the more pearlitic the structure. The micro-structure of cast iron may be examined by preparing the specimen by polishing and etching with a 5 per cent. solution of picric acid in alcohol.

The structure of grey cast iron consists of graphite and pearlite in a silicon-ferrite matrix, the black lines of the graphite, and grey-patches of pearlite showing up against the

* Also see Figs. 160 and 161 for micrographs of motor cylinder cast irons.

ghter silicon-ferrite matrix (Fig. 155). Figs. 156 and 157 show
ıe well-laminated pearlite and the graphite flakes in cast iron,
ıe latter photograph being more highly magnified.

G 156.—CAST IRON, SHOWING GRAPHITE AND WELL-LAMINATED PEARLITE × 100.



G. 157.—CAST IRON, SHOWING GRAPHITE AND WELL-LAMINATED PEARLITE (HIGH MAGNIFICATION). × 400.

In the case of whiter cast irons, the grey matrix consists of
ːarlite, with white patches of iron-phosphorus eutectic
'ig. 158).

The amount of pearlite present is proportional to the com-

and softer, weaker in mechanical properties, but more fusible than the white or mottled irons.

The following is a typical composition of a grey cast iron: Iron [90·38], Carbon (combined) [1·00], Carbon (graphitic) [2·66], Silicon [3·00], Sulphur [1·20], Phosphorus [0·90], Manganese [0·86].

The presence of aluminium and silicon in cast iron has the effect of hindering the combination of the carbon, and thus causes the separation of the graphite, so that irons containing much silicon are of the greyer varieties; the effect of the presence of this element will be considered more fully later.

FIG. 155.—GREY OR WEAK CAST IRON. ETCHED. × 50.

Microstructure of Cast Irons.*—The combined carbon in cast irons is present in the form of carbide of iron, or pearlite, and the greater the proportion of combined carbon the more pearlitic the structure. The micro-structure of cast iron may be examined by preparing the specimen by polishing and etching with a 5 per cent. solution of picric acid in alcohol.

The structure of grey cast iron consists of graphite and pearlite in a silicon-ferrite matrix, the black lines of the graphite, and grey-patches of pearlite showing up against the

* Also see Figs. 160 and 161 for micrographs of motor cylinder cast irons.

[90·6], Carbon (combined) [1·59], Carbon (graphitic) [1·31], Silicon [2·17], Sulphur [1·48], Phosphorus [1·17], Manganese [1·60]. The fracture is a dull white, with pale greyish specks and a line of white around the edge of the fracture.

White Cast Iron.—In this iron the carbon chiefly exists in the combined form; in the whitest cast irons the percentage of combined carbon varies from 2 to 4.

The metal is very hard, close grained, silvery white in fracture, and possesses good wearing and polishing qualities; it is less fusible, and does not take such good impressions from the mould as in the case of the greyer irons.

The following is a typical composition of a medium white pig iron suitable for commercial purposes: Iron [89·40], Carbon (combined) [2·46], Graphite [0·87], Silicon [1·12], Sulphur [2·52], Phosphorus [0·91], Manganese [2·72].

It is usually specified that for white, close-grained hard irons, that the silicon must lie between the limits of 1·2 and 1·6 per cent., whilst the sulphur should not exceed 0·095 per cent., and the phosphorus and manganese each below 0·7 per cent.

For chilled iron, and for hard white irons, manganese up to 1·3 per cent. is an advantage; above this amount tends to make the iron weak.

Classification of Commercial Pig Irons.

There are six different classes of cast iron used in commerce, varying from No. 1, which is the greyest, through the mottled (Nos. 4 and 5), to No. 6, which is the hardest and whitest.

No. 1 *Pig Iron* has a dark grey fracture, with a high metallic lustre, and large graphitic crystals; it is used solely for foundry purposes, being very fusible but deficient in strength.

No. 4 *Pig Iron,* sometimes called "bright," has a light grey fracture, with small crystals, having little lustre; it is not very fusible, and is chiefly used for wearing parts, and for making iron and steel.

No. 5 *Pig Iron* is the *Mottled* type.

No. 6 *Pig Iron,* or *white,* has a white fracture, with little or

TABLE XLVII.

Analyses of Various Cast Irons.*

Total Carbon.	*Combined Carbon.*	*Graphitic Carbon.*	*Silicon.*	*Manganese.*	*Phosphorus.*	*Sulphur.*	*Purpose for which used.*
3·35	0·78	2·57	1·89	0·39	0·70	0·09	Automobile cylinders.
3·17	0·45	2·72	2·00	0·39	0·65	0·13	
2·7 to 3·2	0·6 to 0·8	2·0 to 2·4	1·5 to 2·0	0·4 to 0·6	0·3 to 0·5	0·08	Piston rings.
3·0 to 3·5	—	—	1·7 to 2·3	0·6 to 0·8	0·4 to 0·5	0·08	Automobile castings.
3·0 to 3·5	0·2 to 0·5	2·5 to 3·0	1·5 to 2·3	0·6 to 1·0	0·4 to 0·6	0·08	Car castings (grey iron).
2·6 to 3·6	0·8 to 1·4	1·8 to 2·2	0·75 to 1·25	0·8 to 1·2	0·2 to 0·4	·08 to 0·1	Chilled castings.
2·5 to 3·5	0·7 to 1·3	1·7 to 2·2	1·75 to 2·25	0·6 to 1·0	0·2 to 0·4	0·07	Chills.
3·0 to 3·3	—	—	1·0 to 1·7	0·7 to 0·9	0·2 to 0·4	0·08	Gas-engine cylinders.
2·7 to 3·1	—	—	1·2 to 1·7	0·7 to 0·9	0·3 to 0·5	0·09	Steam-engine cylinders.
Low	—	—	1·25 to 1·50	0·6 to 0·8	0·20	0·07	Drop-hammer dies.
2·8 to 3·6	0·4 to 0·6	2·8 to 3·0	1·25 to 1·75	0·6 to 0·8	0·3 to 0·5	0·10	Engine bedplates.
2·7 to 3·5	0·4 to 0·6	2·6 to 2·9	1·5 to 2·25	0·5 to 0·7	0·4 to 0·6	0·08	,, flywheels.
2·7 to 3·4	0·4 to 0·6	2·3 to 2·8	2·2 to 2·5	0·5 to 0·7	0·4 to 0·5	0·07	Automobile engine flywheels.
Low	—	—	2·2 to 2·5	0·6 to 1·0	0·20	0·06	Fire-grate bars.
—	—	—	0·75 to 1·5	to 0·6	to 0·22	to 0·04	Pig for malleable castings.
—	—	—	2·0 to 2·5	to 0·7	to 0·7	to 0·15	Brake shoes.
2·8 to 3·0	0·45 to 0·6	—	1·2 to 1·5	0·5 to 0·8	0·4 to 0·6	to 0·09	Hard iron for heavy work.
3·0 to 3·2	0·35 to 0·45	—	1·5 to 2·0	0·5 to 0·8	0·4 to 0·6	to 0·08	Medium iron for general work.
—	—	—	2·2 to 2·8	to 0·7	to 0·7	to 0·08	Soft iron castings.
3·3 to 3·8	0·1 to 0·2	3·2 to 3·6	2·5 to 2·8	0·5 to 1·0	1·3 to 1·5	0·04	Thin ornamental work.
3·3 to 3·8	0·4 to 0·5	3·0 to 3·2	2·0 to 2·3	0·5 to 1·0	1·0 to 1·3	0·06	Medium size castings.
Low	—	—	1·75 to 2·0	0·50 to 0·7	0·30	0·08	Friction clutches.
—	—	—	1·0 to 1·5	0·8 to 1·0	0·3 to 0·5	0·08	Gears heavy.
—	—	—	1·5 to 2·0	0·7 to 0·9	0·4 to 0·6	0·08	,, medium.
—	—	—	2·0 to 2·5	0·6 to 0·8	0·5 to 0·7	0·08	,, light.
—	—	—	1·75 to 2·25	0·6 to 0·8	0·5 to 0·7	0·09	Pulleys heavy.
—	—	—	2·25 to 2·75	0·5 to 0·7	0·6 to 0·8	0·08	,, light.
—	—	—	1·75 to 2·25	0·6 to 0·8	0·3 to 0·5	0·08	Valves, small.
—	—	—	2·0 to 2·5	0·5 to 0·7	0·6 to 0·8	0·08	Radiators.
—	—	—	1·25 to 1·5	0·6 to 1·0	0·20	0·06	Ingot moulds.
—	0·8 to 1·0	—	1·0 to 1·3	—	2·0 to 0·3	0·06	Gun iron.

* For other information see Kent's "Mechanical Engineers' Pocket-Book."

no lustre, and is granulated with a radiating crystalline appearance. It is extremely hard and brittle.

The above irons are usually blended together in various proportions according to the nature of the casting required. Most of the ordinary castings of commerce are made of Nos. 1, 2, 3, and 4, in different proportions.

The following table shows the results of an analysis* of the compositions of various cast irons, and gives the most suitable composition for the specified purposes:

TABLE XLVIII.

COMPOSITIONS OF CAST IRON FOR DIFFERENT PURPOSES.

Purpose.	*Combined Carbon.*	*Graphitic Carbon.*	*Silicon.*
Greatest softness	0·15	3·1	2·5
,, hardness	—	—	under 0·8
,, general strength ..	0·50	2·8	1·42
,, stiffness	—	—	1·0
,, tensile strength ..	0·47	—	1·8
,, crushing strength	over 1·0	under 2·6	about 0·8
,, transverse strength	0·7	—	1·5

Effect of Silicon.

It has already been stated that silicon, when present in any appreciable amount (from 2 to 4 per cent.), has the effect of causing the carbon to remain in the uncombined or graphitic state. The proportions of silicon for the greatest tensile, crushing, and bending strengths appear to lie between 1·4 and 2 per cent.; between 2 and 3 per cent. of silicon makes the metal softer and greyer.

Fig. 159 shows clearly in a graphical manner how the proportion of silicon present affects the tensile and crushing strengths and the hardness of cast iron.

Effect of Manganese† and Chromium.

When either of these two elements is present in cast iron

* Trans. Iron and Steel Institute, 1885 (Turner).

† Ferro-manganese is a metallurgical product containing over 50 per cent. of manganese. Spiegeleisen contains from 10 to 30 per cent. manganese. (See also Appendix I.)

the carbon present tends to remain in the combined state; manganese should not exceed about 1 per cent., or brittleness results. Cast iron with 1 per cent. of manganese is used for chilled rolls. The shrinkage of cast iron is increased by this element.

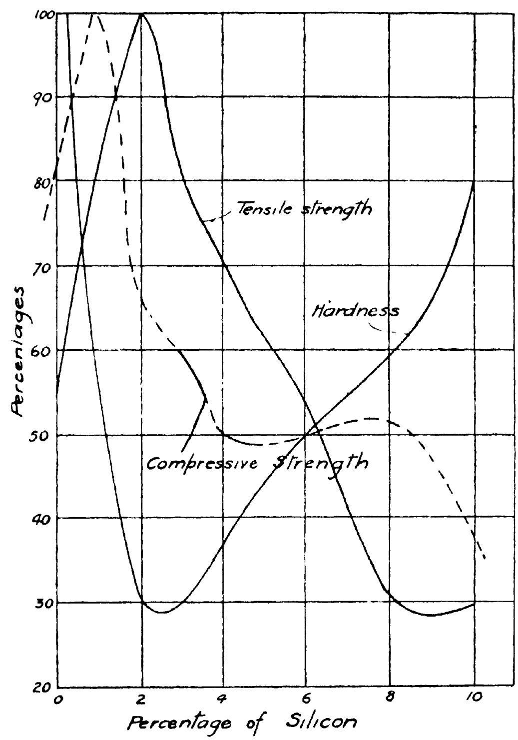


FIG. 159.—INFLUENCE OF SILICON ON PIG IRON.

Effect of Phosphorus.

The presence of phosphorus in a small amount (below 0·8 per cent.) tends to make the metal more fluid, or fusible, and is an advantage for thin or sharp castings; too much phosphorus produces brittleness.

Effect of Copper.

Copper is sometimes found in pig iron made from ores containing copper; its effect when present from 0·1 to 1 per cent. is to close the grain without appreciably affecting the brittleness.

Effect of Aluminium.

When aluminium is added to molten cast iron (from 0·2 to 1 per cent.) it increases the fluidity, and tends to reduce the oxides. When added to grey iron it weakens it.

Effect of Vanadium.

Vanadium in small quantities (from 0·05 to 0·20 per cent.), when added to molten cast iron, acts as a deoxidizer, and also greatly increases the strength of the resulting iron.

Effect of Titanium.

The addition of about $2\frac{1}{2}$ per cent. of a titanium-iron alloy, containing about 10 per cent. of the former element, to molten cast iron gives an increase in strength of from 20 to 30 per cent. to the resulting iron. Part of the titanium reacts with any oxygen or nitrogen present in the metal, and thus purifies it, but does not remain in the metal.

Mechanical Properties of Cast Iron.

The behaviour of cast iron in both tension and compression has already been discussed on page 87. To recapitulate, it may be stated that cast iron is between four and five times as strong in compression as in tension, and exhibits no real elastic strain, so that stresses are not proportional to strains except for very small stresses of a few tons per square inch. The value of the Modulus of Elasticity is given by Unwin as varying from 6400 to 7500 tons per square inch, whilst the Modulus of Rigidity ranges from 3400 to 3000 tons per square inch.

The *tensile strength* of cast iron may be as low as 4 tons per square inch for very grey varieties, and as high as 20 tons per

square inch; but for good cast iron, suitable for castings, it lies between 8 and 12 tons per square inch. The strength of cast iron depends, not only upon the chemical composition, but upon the size and shape of the casting, the pouring temperature, and rapidity of cooling. In general, small, rapidly cooled castings, or chilled castings, are stronger than large, slowly cooled castings of the same metal.

The *compressive strength* may vary from 20 to nearly 100 tons per square inch; but for average foundry iron it lies between 40 and 60 tons per square inch.

The longitudinal extensions and compressions of cast iron vary from 0·000133 to 0·000156 inch per inch length, per ton per square inch load.

The Admiralty transverse* test for cast iron specifies that a 1 inch square bar of 1 foot span should support a central load of 2000 pounds without fracture; this corresponds to a bending strength of about 9 tons per square inch.

The ordinary foundry test is to support a planed rectangular bar of 2 inches depth and 1 inch width at its ends, 3 feet apart, and load it centrally; it should require between 25 and 32 cwts. to fracture it for a good quality iron, from 10 to 20 cwts. for grey and weaker irons, and from 30 to 40 cwts. for the best grades.

Physical Properties of Cast Iron.

The specific gravity of cast iron varies from 6·8 in the case of the dark grey foundry iron to 7·35 for the mottled, and 7·60 for the white grade, the corresponding weights per cubic foot being 425, 458, and 474 pounds respectively.

The melting-point of cast iron is about 1500° C., the specific heat being 0·140 for grey iron, and 0·127 for white iron.

The amount of contraction upon cooling depends upon the size and shape of the casting and upon the quality of the iron.

The shrinkage of cast iron depends upon its composition, and is increased by the presence of manganese when more

* For other information regarding this mode of testing see pp. 139 and 208.

than about 0·7 per cent. is included. The shrinkage is greatest for white and mottled irons, and least for soft irons.

The shrinkage also depends upon the amount of silicon and on the cross-section of the casting, decreasing as the section and the percentage of silicon increase.

The following table* shows the general nature, and the amount of the variation:

TABLE XLIX.

EFFECT OF SILICON AND SECTIONAL AREA ON SHRINKAGE OF CAST IRON.

Percentage of Silicon.	*Size of Square Bars.*				
	0·5 in.	1·0 in.	2·0 in.	3·0 in.	4·0 in.
	Shrinkage, in Inches per Foot.				
1·00	0·178	0·158	0·129	0·112	0·102
1·50	0·166	0·145	0·116	0·099	0·088
2·00	0·154	0·133	0·104	0·086	0·074
2·50	0·142	0·121	0·091	0·072	0·060
3·00	0·130	0·109	0·078	0·058	0·046
3·50	0·118	0·097	0·065	0·045	0·032

Thin cylinders contract only about $\frac{1}{16}$ inch per foot, whereas heavy thick pipes contract about $\frac{1}{8}$ inch per foot; it is usual for ordinary work to allow for a shrinkage of $\frac{1}{8}$ inch per foot. The fractional cubical contraction in the case of cast iron is given by Unwin as $\frac{1}{32}$, and the fractional linear contraction as $\frac{1}{97}$.

In the case of well-dried pinewood patterns, the weight of the casting (in cast iron) is approximately equal to sixteen times the pattern weight.

Applications to Automobile and Aircraft Work.

Cast iron is chiefly employed for cylinder castings, cylinder liners, pistons, piston rings, back-axle casings, brake shoes,

* W. J. Keep, Proc. Amer. Soc. Mech. Engrs., xvi., 1082.

and certain brackets upon the chassis members and miscellaneous wearing parts.*

In the case of *sleeve-valve* engines, the sleeves are made of a good grade of cast iron, and the same metal for liners of cylinders made of aluminium alloy, the liners being shrunk into place and held by studs to the outer casting. Fig. 160 shows a typical sleeve-valve iron micrograph.

The *sleeves* are made of a tough open-grained cast iron derived from best selected Swedish iron, of very low phosphorus and sulphur content. In addition, the high total

FIG. 160.—CAST IRON FOR SLEEVE VALVE. ETCHED WITH 5 PER CENT NITRIC ACID IN ALCOHOL $\times$ 24.

carbon in the sleeve metal brings about the formation of a large quantity of free graphite, which assists in the lubricating and wearing qualities of the sleeves.

A standard transverse bar, loaded in the centre, should have a breaking load varying from 24 to 28 cwt.

For *piston rings* the metal should be fairly elastic, and of good wearing qualities. The iron used should be crucible, melted in a pot furnace in a special manner, in the form of a cylindrical piston pot, the moulds being accurately machined to size. The grain should be fairly fine; the castings being

* For compositions of automobile irons see Table 300.

chilled at a regular temperature. It is essential to specify fine limits for the permissible quantities of silicon, carbon, and phosphorus contents.

Fig. 161 shows a micrograph of an automobile cylinder material.* Motor engine cylinders and pistons are usually sand cast in dry-sand moulds from specially selected cold blast and part mine irons; the sand cores being free from wire binders, and easily withdrawn. The metal should have a low carbon content and possess a fine grain, so that there is no risk of porosity.

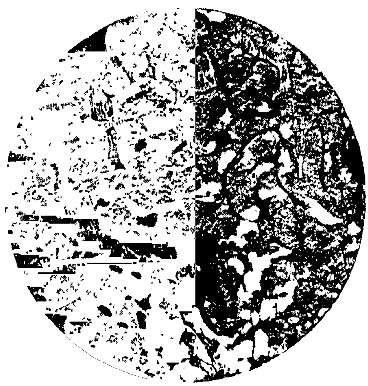


FIG. 161.—CAST IRON FOR AUTOMOBILE CYLINDER. VERTICAL ILLUMINATION. ETCHED WITH 5 PER CENT. NITRIC ACID IN ALCOHOL. × 200.

A specified test is that each cylinder should withstand an hydraulic test of 100 pounds per square inch without leaking, and that a standard transverse bar should fracture with a central load of from 27 to 30 cwt.

The Szèkely Casting Process.

A process invented by Dr. Szèkely for producing castings in metallic moulds in such a manner that the metal is unchilled by the moulds gives hard close-grained castings free from chill.

The castings, which are almost identical in size with the

* "Materials for Motor-Bus Construction," *Engineering*, January, 1917.

patterns themselves, have a very smooth surface, and require practically no fettling.

The metal mould consists of a number of parts which fit together at the machined joints only, the surfaces forming the walls of the mould being left as cast. The joints themselves also act as vents for the escape of the gases generated during the pouring process. It is stated that the results obtained are due to the use of the special compound, consisting chiefly of paraffin and French chalk, which is used for coating the mould.

Automobile castings for cylinders, pistons, and other parts, can be quickly and accurately made by this process.

Chilled Cast Iron.

It is found, in the case of most cast metals that the rate at which the metal is cooled after casting has a considerable influence upon its mechanical properties.

In ordinary sand casting the sand is a poor heat conductor, and slow cooling only occurs; whereas if the mould is made of a metal suitably faced with a loam wash much more rapid cooling occurs, and the casting has a silvery fracture and is extremely hard. It is quite possible to arrange for certain parts of an iron casting to be chilled, where any abrasive or wearing action occurs, and for other parts to be left in the softer condition, by inserting metal portions in the mould.

Metal moulds of cast iron and steel are used for chill-castings.

Table L. gives a few typical analyses of chilled cast iron.

3. **Malleable Cast Iron.**

Malleable iron castings have been used somewhat extensively in connexion with automobile work, especially in America, and their use appears to be increasing at the present time. Ordinary commercial malleable cast iron is obtained by heating iron castings to a red heat in contact with oxide of iron, or powdered red hæmatite, for a period varying from a few hours to two or three days; in this way part of the carbon

TABLE L.

ANALYSES OF CHILLED CAST IRON.

Description.	*Combined Carbon.*	*Graphitic Carbon.*	*Total Carbon.*	*Silicon.*	*Manganese.*	*Sulphur.*	*Phosphorus.*
Charcoal Pig ¼ inch chill	0·4 to 0·9	2·5 to 3·3	2·8 to 3·8	1·3 to 1·7	0·5 to 1·0	0·03 max.	0·3 to 0·4
,, ,, ½ inch ,, ...	0·5 to 1·0	2·3 to 2·7	2·8 to 3·7	1·0 to 1·5	0·5 to 1·0	0·03 max.	0·3 to 0·4
,, ,, ¾ inch ,, ...	0·8 to 1·2	2·0 to 2·5	2·8 to 3·7	0·8 to 1·2	0·5 to 1·0	0·035 max.	0·3 to 0·4
,, ,, 1 inch ,, ...	0·9 to 1·4	1·8 to 2·2	2·8 to 3·6	0·5 to 1·0	0·3 to 0·7	0·035 max.	0·3 to 0·4
Chills	—	—	3·0 to 3·5	1·75 to 2·25	0·6 to 1·0	0·07	0·2 to 0·4
Chilled castings	—	—	2·8 to 3·8	0·7 to 1·25	0·6 to 1·2	0·08 to 0·1	0·2 to 0·4
Chilled wheels	0·6 to 0·8	2·8 to 3·1	3·5 to 3·7	0·6 to 0·7	0·5 to 0·6	0·08 to 0·1	0·3 to 0·4

in the cast iron is reduced or eliminated by its conversion with the oxide into carbon monoxide, or carbon dioxide, and the resulting metal approximates in composition to low-carbon steel or wrought iron. It can be bent and hammered to a certain extent in a similar manner to wrought iron.

Tensile tests* of malleable iron made from cast iron having a tensile strength varying from 6·5 to 13·1 tons per square inch, with a mean value of 10·1 tons per square inch, showed that the tensile strength varied from 14 to 20 tons per square inch, with a mean value of about 16 tons per square inch. The elongation on 5 inches varied from 0·8 to 5·6, being about 2·5 upon the average. The crushing strength varied from 48 to 71·5 tons per square inch.

Malleable iron castings, for automobile and similar work, are usually made from crucible-melted cast iron, although cupola, air, and open-hearth furnace irons are used in much of the malleable work.

A high degree of skill and metallurgical knowledge are necessary in order to ensure the correct annealing and thermal treatments.

Compositions.

For malleable castings a white grade of cast iron is employed —that is, one with more combined carbon; the metal melts at a lower temperature, and also cools more rapidly.

The compositions of pig irons for malleable castings, as given by analyses of typical castings for both European and American practice, are given in Table LI. on the opposite page.

The total amount of combined carbon should be about 3 per cent. in good malleable castings, whilst the amount of graphitic carbon should be as small as possible, as its presence is associated with a weakening effect.

The amount of silicon present affects the casting and pouring temperatures; it should be a minimum for large castings

* Professor P. Ricketts, *Van Nostrands' Magazine*, 1885. Also see *Journ. Iron and Steel Inst.*, vol. ii., 1915 (Dr. Hatfield); "Cast Iron in the Light of Modern Research" (Griffin and Co.); *Cassier's Magazine*, 1907 (R. Moldenke).

TABLE LI.

Compositions of Typical Pig Irons for Malleable Iron Castings.

Description.		*Carbon per Cent.*	*Silicon per Cent.*	*Manganese per Cent.*	*Phosphorus per Cent.*	*Sulphur per Cent.*
English (Western) mixture	White	3·20	0·6	0·10	0·05	0·30
	Mottled	3·45	0·85	0·10	0·05	0·1 to 0·2
English (Eastern) mixture	White	3·10	0·45	0·40	0·05	0·25
	Mottled	3·40	0·5 to 0·8	0·60	0·05	0·15
Average black heart castings* ..		2·8 to 3·8	0·6 to 1·0	0·2 to 0·5	0·06‡	0·25‡
Average European malleable castings (Reamur) ..		2·6 to 4·0	0·6 to 0·9	0·3 to 0·5	0·08‡	0·25‡
Average American practice† ..		2·75 to 3·75	0·45 to 1·00	0·30	0·08‡	0·225‡

(namely, from 0·35 to 0·45 per cent.) and a maximum for small castings (from 1·0 to 1·25 per cent.). The average amount of silicon for medium castings is 0·6 to 0·8 per cent.

The effect of manganese is to strengthen the iron and to reduce the shrinkage; if too little manganese is present a weak casting with high shrinkage results. The average manganese content should be about 0·3 to 0·4 per cent.

The sulphur and phosphorus contents should not exceed 0·08 and 0·25 per cent. respectively.

The shrinkage of the hard casting is about 0·25 inch per foot, or about twice that of grey iron; and, as previously mentioned, for minimum shrinkage a relatively high manganese content is essential.

The castings are allowed to cool in the sand until a black heat is reached and are then shaken out, and when cool are

* The average strength results for these castings are Tensile strength, 20 to 23 tons per square inch; elongation on 2 inches, 8 to 12 per cent.; reduction of area, 10 to 13 per cent.

† For small castings the silicon may go up to 1·25 per cent., whilst for heavy ones it may drop as low as 0·35 per cent.

‡ Maximum.

cleaned of the sand either in an exhaust tumbler or by the sand-blast.

The "annealing" process, as it is termed, consists in heating the castings in contact with oxides of iron in special annealing ovens, maintained at about 800° to 900° C. for three or four days, after which the fire is allowed to slowly die down, until at the end of eight or nine days the process is complete; attempts at shortening this period by employing higher temperatures have not, as yet, been satisfactory.

The "black heart" variety of malleable iron is largely used for automobile work, and is so called from the appearance of the fracture, which shows a steel-coloured contour with a black velvety core; its tensile strength compares favourably with that of steel, although the elongation is appreciably less.

The average mechanical properties* of this iron are as follows—namely:

Ultimate Tensile Strength	= 23 tons per square inch.
Elastic Limit	= 14 to 17 tons per square inch.
Elongation	= 13 per cent.
Contraction in Area ..	= 18·5 per cent.

The British Admiralty specification for malleable cast iron requires a minimum tensile strength of 18 tons (or 40,320 pounds) per square inch, with an elongation of 4 per cent. in 3 inches, on a test bar of 1 inch by $\frac{3}{8}$ inch rectangular section. It is also stipulated that the specimen must bend to an angle of 90 degrees round an arc of 1 inch radius without exhibiting cracks or other signs of fracture.

The following specifications are those adopted by the American Society for Testing Materials:

Specification for Malleable Cast Iron.

Process of Manufacture.—Malleable iron castings may be made by the open-hearth, air-furnace, or cupola process. Cupola iron, however, is not recommended for heavy or important castings.

Chemical Properties.—Castings for which physical requirements are specified shall not contain over 0·06 per cent. of sulphur, or over 0·225 per cent. of phosphorus.

* "Commercial Steels and their Heat Treatment," by J. B. Hoblyn (Proc. I.A.E., 1918).

Physical Properties—(1) *Standard Test Bar.*—This bar shall be 1 inch square and 14 inches long, cast without chills, and left perfectly free in the mould. Three bars shall be cast in one mould, heavy risers ensuring sound bars. Where the full heat goes into the castings, which are subject to specification, one mould shall be poured two minutes after tapping into the first ladle, and another mould shall be poured from the last iron of the heat.

Moulds shall be suitably stamped to ensure identification of the bars, the bars being annealed with the castings. Where only a partial heat is required for the work in hand, one mould shall be cast from the first ladle used and another after the required iron has been tapped.

(2) Of the three test bars from the two moulds required for each heat, one shall be tested for tensile strength and elongation, the other for transverse strength and deflection. The other remaining bar is reserved for either tensile or transverse test in case of failure of the other two bars to come up to requirements. The halves of the two bars broken transversely may also be used for the tensile test.

(3) Failure to reach the required limit for the tensile test with elongation, as also for the transverse test with deflection, on the part of at least one test, rejects the castings from that heat.

(4) *Tensile Test.*—The tensile strength of a standard test bar for casting under specification shall not be less than 40,000 pounds per square inch. The elongation measured in 2 inches shall not be less than $2\frac{1}{2}$ per cent.

(5) *Transverse Test.*—The transverse strength of a standard test bar on supports 12 inches apart, pressure being applied at the centre, shall not be less than 3,000 pounds, with deflection at least $\frac{1}{2}$ inch.

Test Lugs.—Castings of special design or special importance may be provided with suitable lugs at the option of the inspector. At his request, at least one of these lugs shall be left on the castings for his inspection.

Annealing.—(1) Malleable castings shall neither be over nor under annealed. They must have received their full heat in the oven at least sixty hours after reaching that temperature.

(2) The saggars shall not be dumped until the contents shall at least be black-hot.

Finish.—Castings shall be true to pattern, free from blemishes, scale, or shrinkage cracks. A variation of $\frac{1}{16}$ inch per foot shall be permissible. Founders shall not be held responsible for defects due to irregular cross-sections and unevenly distributed metal.

Inspection.—The inspector representing the purchaser shall have all reasonable facilities given him by the founder to satisfy him that the finished material is furnished in accordance with these specifications. All tests and inspections shall be made prior to shipment.

Mitis Castings.—These are wrought iron castings made by adding from 0·05 to 0·09 per cent. of aluminium to Swedish wrought iron which has been melted. The effect of the alu-

minium is to lower the melting-point of the iron by some 300° or 400° C. The iron is melted in a petroleum fired furnace in crucibles of fireclay or plumbago.

Mitis castings are stated to possess all the properties of best wrought iron, but are free from stratification, and are homogeneous in structure.

The tensile strength is said to be up to 20 per cent. higher than that of wrought iron, whilst the ductility is about the same.

Semi-Steel.

Semi-steel is the name given to cast iron made from pig iron melted in the furnace with the addition of from 20 to 30 per cent. of steel scrap; ferro-manganese is also sometimes added. The addition of the steel dilutes the silicon of the pig iron and converts some of the graphitic to combined carbon.

Semi-steel is rather a misnomer, being simply strong cast iron low in silicon, sulphur, and phosphorus, and containing manganese.

The steel should be in the form of punchings and shearings, and good results are obtainable from the cupola type of melting furnace.

Carbon Steels.

Steel is the name given to wrought or nearly pure iron combined with a proportion of carbon, silicon, phosphorus, and other elements. The different carbon steels of commerce vary widely in their physical and mechanical properties.

In general, commercial steels, which for most purposes have practically replaced wrought iron, are of a uniform and homogeneous texture of finer grain than iron.

Steels containing less than 0·2 per cent. of carbon are not appreciably hardened by quenching from a red heat, but are readily weldable, and are similar to wrought iron in their properties, but are more homogeneous and reliable.

Steels containing from 0·20 to 0·40 per cent. of carbon, known as *Mild Steels*, are very widely employed for engineering

structural work, being much stronger and more ductile than wrought iron.

Such steels are capable of being appreciably hardened by quenching from a red heat, and can be welded, but with rather more difficulty than in the case of pure iron.

Steels containing over 0·4 per cent. of carbon are capable of being hardened and tempered,* and are stronger and harder† than the preceding steels in proportion to their carbon content.

The maximum percentage of carbon in commercial steels is about 1·5, and corresponds to the composition of cast, tool, and file steels, which when hardened are extremely hard, and are capable of scratching glass, although at the same time they are brittle.

Specific Gravity.—The specific gravity of steel is affected by its composition and by the heat-treatment to which it is subjected.

For 0·3 per cent. carbon steel, the S.G. is 7·855, whilst for 1·08 per cent. carbon steel, it is 7·803 in the ingot state; rolling and mechanical treatment increase the density by from 0·5 to 1·2 per cent.

A good average value of the S.G. for mild steel is 7·85, a cubic foot weighing 490 pounds.

Methods of Manufacture.

The three principal methods of making steel are as follows —namely: (1) The Cementation Process, (2) The Bessemer, and (3) The Siemens-Martin or Open-Hearth Process.

The Cementation Process.—In this method steel is produced by adding carbon to wrought iron. Bars of wrought iron, surrounded by charcoal in a fireclay box, are heated to redness for a long period, the carbon gradually penetrating inwards from the outside; the period of time required to carburize a bar of iron of ½ inch diameter is about thirty-six hours.

The steel produced by this process is known as *Blister Steel*, owing to its blistered appearance when withdrawn from the furnace. This steel is broken up into pieces about 18 inches

* See p. 321. † See pp. 322 and 323.

long, which in turn are bound together with steel wire in bundles, or are piled; the bundles or piles are heated to a welding heat, and forged under a mechanical or steam hammer, and rolled. The resulting product is called *Shear Steel.* If the above process be repeated upon this steel it becomes *Double Shear Steel.*

Cast Steel is obtained by melting the broken pieces of blister or shear steel, which are initially produced from a pure brand of wrought iron, and casting into ingots; fireclay crucibles containing graphite are used for the purpose of melting, and each pot usually contains from 40 to 60 pounds of steel. The best grades of cast steel, which are produced from the purest brands of iron, containing only minute quantities of sulphur and phosphorus, after having been obtained in the ingot form, are reheated and rolled into bars, which are then given the name of *Tool Steel.* Both cast and tool steel contain a higher percentage of carbon* than any of the other carbon steels, and are therefore capable of greater hardness and strength when suitably treated.

The Bessemer Process.—In this process steel is obtained from cast iron by removing most of the carbon from cast iron (or decarburizing). Cast iron is melted in a "converter," and a blast of air is then sent through the molten metal; the oxygen of the air decarburizes (and oxidizes the silicon of) the iron, the remaining metal being nearly pure iron. In order to convert this molten iron into steel a charge of *spiegeleisen*—which is a mixture of iron, carbon, and manganese—or of ferro-manganese is introduced, after the air blast is stopped, and after the elapse of a certain period the molten metal is poured out into moulds to form ingots. The ingots are then reheated and rolled into bars of various sections.

Most of the steel used for rails and structural work is made by the Bessemer process.

The Siemens-Martin Process.—This method consists in melting a mixture of cast iron and wrought iron, or of cast iron and certain iron ores and fluxes, in the hearth of a reverberatory

* See Table LII.

furnace, so that part of the carbon of the cast iron is retained by the wrought iron and the resulting steel contains the correct amount of carbon for its specified purpose.

The lining of the furnace and the fluxes are usually arranged to contain strongly basic substances, such as lime and iron oxide, in order to remove the phosphorus, and the process is then known as the *Basic Open Hearth* one.

If the lining or fluxes contain much silica the removal of the phosphorus is partially prevented, and an acid slag is formed.

Steel made from special ores and irons, in furnaces containing much silica in the linings or slags, are known as *Acid Open Hearth* ones.

Most of the carbon steels used for railway axles, tyres, shafts, structural angles, channels, etc., are made by the Siemens-Martin process.

English Steel Practice.

Prior to 1914 about one-third of the steel production* was made by the "basic" process, and the remaining two-thirds by the "acid" process. The present output of "basic" steel is from two-fifths to three-fifths of the total,† showing a gradual reversion to this method of steel manufacture.

Converters and furnaces lined with ganister or silica bricks —that is, with an "acid" lining—are not suitable for pig-irons containing a high phosphorus content, whereas those lined with "basic" linings of magnesite and calcined dolomite are widely used for high-phosphorus ores and irons, as the lining holds the oxidized phosphorus from the ores, and gives a basic slag.

The adoption and extension of the basic process enables a much wider use to be made of the English iron ores, which are lower in ferric oxide and higher in phosphorus than the imported ores from the Continent, which are chiefly "hæmatites," rich in iron and low in phosphorus.

* About 7½ million tons annually.

† About 10 to 12 million tons, 1918-19.

Classification of Carbon Steels.

Steel may be divided into four principal classes according to the carbon content, as follows:

1. *Soft*, or *Low, Carbon Steel*, which contains from 0·05 to 0·20 per cent. of carbon, and which is not capable of being hardened, but easily weldable.

2. *Medium Carbon Steel*, containing from 0·15 to 0·45 per cent. of carbon; this steel can be slightly hardened, and is weldable.

3. *Hard Carbon Steel*, containing from 0·4 to 0·7 per cent. of carbon, which is capable of being readily hardened, but is weldable with difficulty.

4. *Very Hard Carbon Steel*, which contains from 0·7 to 1·5 per cent. of carbon, is capable of being fully hardened, but which is unweldable.

Typical micrographs of carbon steels are shown in Figs. 128 to 133.

Carbon steels invariably contain small amounts of other elements, such as manganese, silicon, sulphur, or phosphorus, often for a specific purpose, but these steels may conveniently be classified according to their carbon contents and applications, as shown in Table LII.

Effect of Presence of Small Amounts of other Elements.

The effect of relatively large amounts of elements other than carbon will be considered at a later stage under the heading of Alloy Steels; but in connexion with the influence of small quantities of elements such as manganese, silicon, sulphur, etc., in medium and low carbon steels, it is known that these have a certain influence upon the mechanical and physical properties of carbon steel.

Manganese, which is usually introduced in the form of an ore, such as ferro-manganese, during the process of making the steel, for eliminating the silica and iron oxide, often remains in small quantities in the steel. It tends to behave in the same way as carbon in its influence upon the hardness and strength

TABLE LII.

APPLICATIONS OF STEELS OF DIFFERENT CARBON CONTENTS.

Percentage of Carbon.	*Applications.*
0·1 to 0·2	Case-hardening steels, mild steel bars, rails, boilers, bolts, nuts, pins, sheets, tubes, and for general purposes.
0·2 to 0·4	Medium carbon steels, axles, high-speed shafts, lathe spindles, levers, gear shafts, axle tubes, torque tubes; strong bolts, nuts, and pins; "40" ton steel; drop-forgings, pressings, stampings, and castings; rods, tubes, and sheets.
0·4 to 0·5	Automobile steels, steel rails, high-tensile steels; drop-forgings, pressings, stampings; steel castings.
0·5 to 0·6	Tools for hot work and battering tools. Steel castings.
0·6 to 0·7	Tools for hot work and dull edges.
0·7 to 0·8	Battering tools, cold sets, and some forms of reamers and taps; miners' tools, hammers, general dies
0·8 to 0·9	Cold sets, hand-chisels, drills, taps, reamers, dies; smiths' tools, large shear blades, masons' tools.
0·9 to 1·0	Chisels, drills, dies, axes, knives; best all-round tool-steel.
1·0 to 1·10	Axes, hatchets, knives, large lathe tools, small drills and dies, circular culters, small shear blades, large taps, hot sets, ball bearings, balls, and rollers.
1·10 to 1·50	Lathe tools, engraving tools, planing tools, scribers' scrapers, small drills, small culters, small punches.

of the steel. The amount of manganese present in low and medium carbon steels (up to 0·5 per cent. carbon) usually varies from 0·10 to 1·0 per cent.

Table LIII. on p. 320 shows the compositions and mechanical properties of carbon steels containing manganese.

The effect of *silicon* is to make steel harder, and, up to a certain amount, is considered an advantage in connexion with the production of sound material and for its deoxidizing qualities. Medium steel specifications usually limit the maximum permissible amount of silicon to about 0·06 or 0·08 per cent. Up to 0·10 per cent. of silicon is allowed in steels for forgings, more especially in connexion with guns, and for hard rails, tyres, and springs.

Silicon is used in making steel castings in order to reduce the temperature of fusion and to prevent blowholes. From 0·10

TABLE LIII.

Effect of Manganese upon the Properties of Carbon Steels.

Material.		*Composition per Cent.*		*Yield Point, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Reduction of Area per Cent.*
		Carbon.	*Manganese.*				
						On 2 inches.	
Acid Bessemer steels, as rolled or forged	A.	0·10	0·56	19·1	25·9	37·1	63·4
	B.	0·27	0·68	26·7	35·8	32·7	58·9
	C.	0·29	0·92	26·6	40·9	25·0	46·8
	D.	0·32	0·67	27·1	39·9	26·6	47·8
	E.	0·44	0·90	30·7	46·6	25·7	48·2
	F.	0·50	0·92	30·6	52·2	19·8	42·2
	G.	0·70	0·90	34·7	59·0	17·9	34·6
	H.	0·75	0·92	36·6	64·2	15·3	30·6
	I.	0·86	1·03	40·6	52·6	1·8	3·3
Boiler plates		0·19 to 0·25	0·45 to 0·63	—	25 to 29	28 to 32*	—
Forgings		0·3 to 0·4	0·75 to 1·0	—	30 to 40	20†	—
Gun steel		0·3	0·5	—	42	23	—
Rails		0·3 to 0·5	0·5 to 1·0	—	35 to 45	12 to 20*	—
Tyre steel		0·25 to 0·65	0·2 to 1·0	—	—	—	—
Axle steel		0·27	1·0	19 to 21	30 to 32	26†	—
Spring steel		0·45	1·0	—	46 (soft)	21†	—
					70 (tempered)	3*	—
Angle and channel steel		0·2 to 0·25	0·5 to 0·6	—	27 to 30	30†	—
Steel castings		0·15	0·40	—	25	30†	—
		0·40	0·70	—	35	12†	—
Case hardening steel		0·12	0·70	20	30	30	65

* On 8 inches. † On 4 inches.

to 0·50 per cent. of silicon is usually present in steel castings.

Phosphorus and *sulphur*, should both be kept as low as possible in the case of steel; neither should be allowed to exceed 0·05 per cent. in low, medium, and hard carbon steels. *Sulphur* above about 0·8 per cent. makes steel "red short,"* but *phosphorus* up to 1·0 per cent. does not appear to affect steel so markedly as in the case of iron.

Small quantities of *copper* and *arsenic* tend to make steel red short.

Mechanical Properties of Carbon Steels.

Low-carbon steels, containing about 0·15 to 0·20 per cent. of carbon, have, in the rolled state, a tensile strength of from 28 to 30 tons per square inch, with a corresponding elongation of about 25 per cent. upon an 8-inch length.

The tensile (and also the compressive and shearing) strength increases with the percentage of carbon, but the plasticity, as indicated by the percentage elongation, diminishes, as also does the contraction in area.

High-carbon steels, containing from 0·8 to 1·0 per cent. of carbon, have, in the rolled or natural form, a tensile strength of from 45 to 55 tons per square inch, with a corresponding extension of from 14 to 8 per cent. upon an 8-inch length, the reduction of area being from about 15 to 10 per cent.

The strength and ductility of a given carbon steel depends to a large extent upon the mechanical treatment which it receives; for example, the tensile strength of a high-carbon steel wire, produced by successive wire-drawings through dies, varies from 80 to 120 tons per square inch, whereas that of the initial rod is about 40 to 50 tons. The mechanical properties also depend very largely upon the hardening or tempering processes to which the steel (if it is a "hardenable" type) has been subjected.

The effect of the carbon content upon the strength and ductility of carbon steels, in the rolled or natural form,† in the

* See p. 290. † *I.e.*, not heat-treated in any way.

case of a number of Bessemer steels tested by Bauschinger is shown graphically in Fig. 162, whilst the tabular results are given in Table LIV.

An examination of the results shows that the elastic limits in tension and compression both increase with the carbon content. The ultimate tensile strength also increases with the amount of carbon, but not in direct proportion.

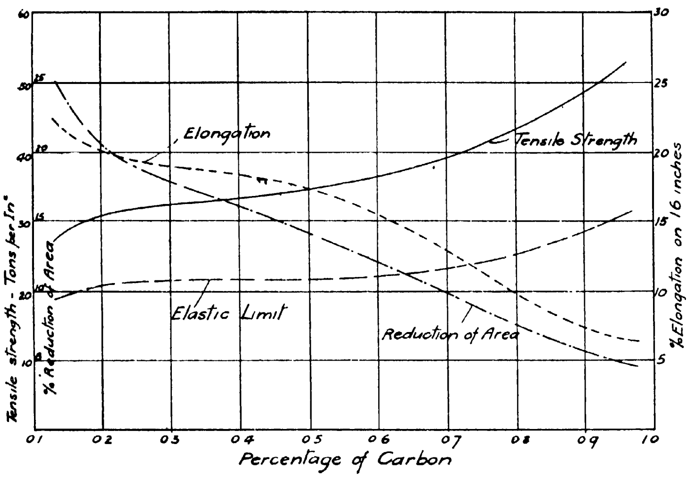


FIG. 162.—EFFECT OF CARBON UPON THE STRENGTH AND DUCTILITY OF STEEL.

The following formula for the tensile strength of carbon steel, in terms of the percentage of carbon C,* is given by Bauschinger:

Ultimate Tensile Strength$=27\cdot6\ (1+C^2)$ tons per square inch.

The percentage elongation and contraction of area both progressively diminish with increased carbon content.

The Moduli of Elasticity† in tension and compression do not appear to vary greatly with the carbon content, although there is a small diminution in their value with increased carbon content.

* See also p. 265.

† Bauschinger's values are now considered to be about 7 or 8 per cent. too high.

TABLE LIV.

EFFECT OF THE CARBON CONTENT UPON THE MECHANICAL PROPERTIES OF CARBON STEELS. (Bauschinger.)

Percentage of Carbon.	*Mean Modulus of Elasticity, Tension E., in Tons per Square Inch.*	*Elastic Limit in Tension, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. in 16 inches.*	*Contraction of Area per Cent.*	*Modulus of Elasticity in Compression, E., Tons per Square Inch.*	*Elastic Limit in Compression, Tons per Square Inch.*	*Ultimate Shearing Strength in Tons per Square Inch.*
0·14	14,300	18·73	28·1	21·8	49·2	17,080	17·65	21·7
0·19	13,780	21·02	30·4	20·1	41·7	16,580	19·20	23·6
0·46	14,300	21·90	33·8	18·1	30·5	14,660	21·85	22·8
0·51	14,040	21·62	35·6	14·3	25·1	14,540	20·64	25·5
0·54	13,720	22·15	35·3	17·8	32·8	16,130	21·85	25·0
0·55	14,100	20·98	35·9	17·6	27·9	15,040	22·22	25·4
0·57	13,720	21·02	35·6	18·4	30·7	14,280	21·85	23·1
0·66	14,480	23·77	40·0	13·7	19·7	15,940	23·95	27·2
0·78	14,980	23·80	41·1	11·4	19·1	14,480	23·95	26·3
0·80	13,660	25·45	45·9	9·0	14·0	14,480	23·20	30·6
0·87	13,900	27·24	46·7	8·1	16·5	14,100	25·00	31·7
0·96	13,820	30·90	52·7	6·6	10·0	14,600	31·75	37·0

The mean value of the Elastic Modulus E, obtained for medium and high carbon steel, as deduced from the results of independent experiments, is about 13,200 tons per square inch.

The Modulus of Rigidity C varies from 5300 to 5700 tons per square inch, according to the percentage of carbon, as shown in Table LIV.

The shearing strength increases with the percentage of carbon in a similar manner to the tensile strength.

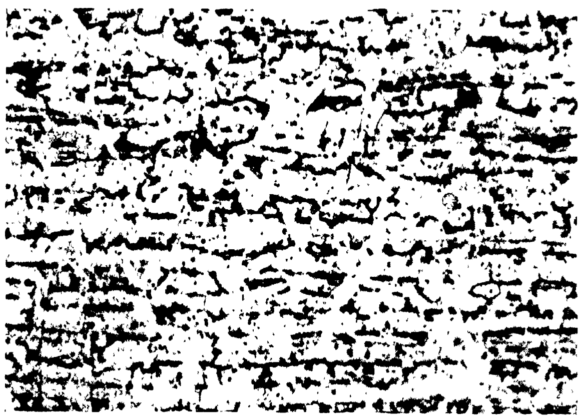


FIG. 163.—SHEET CARBON STEEL. ETCHED. × 500.

Mild Steel Plate and Bar.

The strength of mild steel plate is approximately the same along and across the direction of rolling, although it is slightly greater along the rolling direction, and the percentage elongation is from 10 to 15 per cent. less.

Fig. 163 shows a typical micrograph of sheet steel, in which the effect of rolling on the flow lines can be clearly seen.

The tensile strength of thin plates is usually greater than that of thicker plates in the rolled state, due to the relatively greater hardening effect; the same effect is also found in the case of rolled bars. Thus the tensile strength of a $\frac{3}{8}$-inch

diameter iron bar was found to be 24·1 tons per square inch, whilst that of a 2½-inch diameter bar of the same material was 21·1 tons per square inch.

The tensile strength of good mild steel plates* of from ¼ to ½ inch thickness varies from 25 to 28 tons per square inch, with an elongation of from 25 to 30 per cent. on 4 inches.

The effect of bright drawing mild steel bar, even of low-carbon content, is to increase its tensile strength and hardness, but to reduce its elongation, as the following figures of Gœrens† show in the case of 0·12 per cent. carbon steel:

TABLE LV.

EFFECT OF BRIGHT DRAWING LOW CARBON STEEL.

Treatment.	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Reduction of Area per Cent.*
1. Hot rolled (untreated) ..	26·3	32·7	70·0
2. Subjected to 1 drawing ..	33·6	15·6	66·3
3. Subjected to 2 drawings ..	38·2	10·2	65·8
4. Subjected to 6 drawings ..	53·7	6·0	30·0

The hardness was increased from about 90 to 180, on the Brinell scale, from Condition No. 1 to No. 4.

In Table LVI. the results of tests‡ upon bright drawn mild steel bars also show the hardening effect of rolling in the case of the smallest bar.

Low-Carbon Steel (Case-Hardening).

Steels containing under about 0·15 per cent. of carbon are employed for parts in automobile and aircraft work which require case-hardening after manufacture, and in cases where expense prohibits the use of an alloy steel.

The tensile strength of the material in the untreated state varies from 23 to 33 tons per square inch according to the carbon content.

* Corresponding to a carbon content of from 0·18 to 0·25 per cent.
† "Carnegie Scholarship Memoirs," 1911, No. III.
‡ Manufactured by Messrs. Flather, Ltd., Sheffield.

TABLE LVI.

Tensile Test Results for Bright Drawn Mild Steel Bar (Untreated).

Diameter of Bar.	$1\frac{1}{4}$ *inches.*	$\frac{3}{4}$ *inch.*	$\frac{1}{4}$ *inch.*
Elastic limit (tons per square inch)	29·60	29·81	36·56
Tensile strength (tons per square inch)	32·14	32·68	42·65
Elongation on 2 inches (per cent.)	44·0	33·5	14·0
Reduction of area (per cent.)	52·2	61·0	53·8

The following are the Engineering Standards Committee's Specifications* for low-carbon steels for case-hardening.:

(A) E.S.C. "10" Carbon Case-Hardening Steel.

Chemical Composition :

Carbon	0·08 to 0·14 per cent.
Silicon	not over 0·2 ,,
Manganese	,, 0·60 ,,
Sulphur	,, 0·04 ,,
Phosphorus	,, 0·04 ,,

Check Test.—When normalized at 900° to 920° C. this steel shall pass in every particular the following check test

Tensile breaking strength ..	23 to 28 tons per square inch.
Yield ratio	not less than 50 per cent.
Elongation	,, ,, 30 ,,
Reduction of area	,, ,, 50 ,,

The Brinell hardness number shall be approximately 92 to 112.

(B) E.S.C. "15" Carbon Case-Hardening Steel.

Chemical Composition :

Carbon	0·12 to 0·20 per cent.
Silicon	not over 0·20 ,,
Manganese	0·65 to 1·00 ,,
Sulphur	not over 0·07 ,,
Phosphorus	,, 0·07 ,,

Check Test.—When normalized at 890° to 920° C. this steel shall pass in every particular the following check test

Tensile breaking strength ..	25 to 33 tons per square inch.
Yield ratio	not less than 50 per cent.
Elongation	,, ,, 28 ,,
Reduction of area	,, ,, 50 ,,

The Brinell hardness number shall be approximately 103 to 143.

* "British Standard Specifications for Wrought Steels for Automobiles," June, 1918.

COMPOSITION, TREATMENT, AND MECHANICAL PROPERTIES OF LOW-CARBON STEELS.

Make of Steel and Heat Treatment.	*Composition per Cent.* Carbon.	*Man-ganese.*	*Silicon.*	*Sul-phur.*	*Phos-phorus.*	*Yield Point (Tons per Square Inch).*	*Tensile Strength (Tons per Square Inch).*	*Elonga-tion per Cent.*	*Reduc-tion of Area per Cent.*	*Brinell Hard-ness.*
Vickers' case-hardening mild steel. Normalized at 900° C.	0·14 to 0·20	0·65 to 1·00	0·30 (max.)	0·06 (max.)	0·06 (max.)	15	26 to 34	28	50	111 to 146
Ditto. Carburized to depth of $\frac{1}{32}$ inch and water-quenched twice, from 900° C. and 780° C. respectively.	,,	,,	,,	,,	,,	20	32 to 45	23	55	—
Allen's case-hardening mild steel. As rolled	Corresponds	with	"E.S.C. 10"			16 to 19	28 to 32	33 to 39	60 to 50	110 to 115
Ditto. Carburized at 875° C. and allowed to cool, then reheated to 825° C. and quenched in water. Then reheated again to 750° C. and quenched.						21 to 25	34 to 37	30 to 36	65 to 60	150 to 160
Firth's* case-hardening mild steel. As rolled.	0·12	0·7	—	—	—	20	30	30	65	—
Ditto. Case-hardened core	,,	,,	—	—	—	24	35	25	60	—
Jonas, Colver and Co.'s case-hardening mild steel. As rolled.	—	—	—	—	—	15†	26	38	64	107
Ditto. Case-hardened core	—	—	—	—	—	20	30	30	60	131
Case-hardening steel for chain gear wheels‡ (Swedish charcoal-steel stampings). Untreated.	0·09 to 0·14	0·02 to 0·30	trace to 0·03	0·015 to 0·02	trace only	15 to 18	21 to 25	25 to 30	60 to 70	—

* Dr. Hatfield, "Steels used in Aero Work," *Aero. Journal*, 1918.

† Elastic limit.

‡ "Materials used for Motor Bus Construction," Daimler Co. ... 1918.

Table LVII. gives particulars of the chemical compositions, methods of heat treatment, and mechanical test properties of some typical case-hardening mild steels.

Applications of Low-Carbon Steels.—From the point of view of the automobile and aircraft engineer this steel is not used to any appreciable extent, except for the cheaper, more easily machined parts, subjected to wearing action, and therefore requiring a hard skin or surface. It is primarily used for parts not subjected to high stresses, such as gear-wheels, cam-shafts, pins, levers, spindles, worm and worm-wheels, valve tappets, starting dogs, constant mesh pinions, sliding pinions, cams, etc.

This class of case-hardening steel is fairly easy to carburize to any depth, and if properly treated gives a much harder skin than any alloy steel, but possesses a much lower core tensile strength.

Particulars of case-hardening processes will be found in Chapter VIII.

Low-carbon steel tubes and plates are sometimes used for miscellaneous fittings in automobile work on account of the ease with which they can be manipulated, brazed, and welded.

Medium Carbon Steels [0·2 *to* 0·5 *per cent. Carbon*].

This type of steel is used for inexpensive classes of automobile work, and with suitable heat treatment can be made to give tensile strengths of from 40 to 50 tons per square inch. This steel is also used for bolts, nuts, and washers, for drop-forgings and aeroplane cylinders of rotary or radial type. It is not suitable for case-hardening, but can be heat-treated with advantage.

Steels containing from 0·4 to 0·5 per cent. of carbon are known commercially as "40-ton" steels; it is, of course, possible to obtain such steels by drawing steels of a much lower carbon content, but these are not suitable for the same class of work owing to their greater brittleness (or greater hardness and smaller elongation).

Engineering Standards Committee's Specifications—

1. E.S.C. "20" Carbon Steel.

Chemical Composition :

Carbon	0·15 to 0·25 per cent.
Silicon	not over 0·25 ,,
Manganese	0·40 to 0·85 ,,
Sulphur	not over 0·06 ,,
Phosphorus	,, 0·06 ,,

Check Test.—When normalized at 890° to 920° C. this steel shall pass in every particular the following check test

Tensile breaking strength ..	26 to 34 tons per square inch.
Yield ratio	not less than 50 per cent.
Elongation	,, ,, 28 ,,
Reduction of area	,, ,, 50 ,,

The corresponding Brinell hardness number to be approximately 105 to 149.

2. E.S.C. "35" Carbon Steel.

Chemical Composition :

Carbon	0·30 to 0·40 per cent.
Silicon	not over 0·30 ,,
Manganese	0·50 to 0·85 ,,
Sulphur	not over 0·06 ,,
Phosphorus	,, 0·06 ,,

Check Test.—When normalized at 850° to 880° C. this steel shall pass in every particular the following check test

Tensile breaking strength ..	30 to 40 tons per square inch.
Yield ratio	not less than 50 per cent.
Elongation	,, ,, 25 ,,
Reduction of area	,, ,, 45 ,,

The corresponding Brinell hardness number to be approximately 121 to 179.

Mild Steel Bar for Aircraft Work.

Bright drawn mild steel bar for making aeroplane bolts, nuts, washers, stampings, and forgings, can be readily machined, and the finished objects can be given a good appearance.

Steel of this type should fulfil the following mechanical tests:

Yield point	25 tons per square inch.
Tensile strength	33 to 38 tons per square inch.
Elongation on 2 inches ..	When added together must be equal to not less than 60 per cent.
Reduction of area	

The Brinell hardness number in the untreated state should lie between 155 and 170.

The Izod impact test upon a 10×10 mm. specimen* with a V notch 2 mm. deep, and angle of 45°, clamped at one end, should give an energy absorption of from 12 to 16 foot-pounds when the specimen is struck at 22 mm. above the notch.

It is also usual to specify a bend test upon bars of from ½ inch to ¾ inch diameter—namely, that these shall be bent over through 180°, or double, until the internal radius is equal to the diameter of the test piece and the sides are parallel, as shown in Fig. 52. The specimen should not show any cracks or flaws upon the outer, or tension, side after this test.

Table LVIII. gives the chemical compositions, heat treatments, and mechanical properties of some typical makes of medium carbon steel.

These steels are supplied by the manufacturer in the form of bars, billets, forgings, stampings, castings, tubes, and sheets, and examples of their use may be found in the case of locomotive axles, high-speed shafts, lathe spindles, levers, crankshafts,† connecting rods,† gear shafts, axle tubes, torque tubes or rods, gear levers, etc.

For aircraft work it is usual to specify for 40-ton steel for forgings and stampings, in addition to the tensile test, the following additional hardness and bend tests:

1. The Brinell hardness number should be from 140 to 160 in the untreated state.

2. A circular specimen of from ½ inch to ¾ inch diameter, and of not less than 10 inches long, shall be bent over double until the sides are parallel, and the internal radius of the bend is equal to the diameter of the specimen, without showing any cracks or flaws on the outer surface (*i.e.*, the tension side).

The yield point of 40-ton aircraft steel should not be less than 20 tons per square inch, and the respective ultimate percentage elongation on 2 inches and reduction of area should be about 24 and 40.

* See p. 142 for shape of standard specimen.

† In the cheaper classes of automobile and similar engines.

TABLE LVIII.

Composition, Treatment, and Mechanical Properties of Medium Carbon Steels.

Make of Steel and Treatment.	*Composition per Cent.* Carbon.	Manganese.	Silicon.	Phosphorus.	Sulphur.	*Yield Point (Tons per Square Inch).*	*Tensile Strength (Tons per Square Inch).*	*Elongation per Cent. on 2 Inches.*	*Reduction of Area per Cent.*	*Brinell Hardness.*
Vickers' "medium carbon steel." Normalized at 850° C.	0·25 to 0·35	0·40 to 0·80	0·30 (max.)	0·06 (max.)	0·06 (max.)	16	30	25	45	128 to 170
Ditto. Oil-hardened at 850° C. and tempered at 575° C.	Nickel 0·5	,,	,,	,,	,,	21	35	24	28	152 to 207
Vickers' high-tensile carbon steel. Normalized at 825° C.	0·35 to 0·45	0·50 to 0·80	0·12 to 0·35	0·04 (max.)	0·04 (max.)	18	35 to 45	23	40	149 to 197
Ditto. Oil-hardened at 825° C. and tempered at 575° C.	Nickel 0·5	,,	,,	,,	,,	24	40 to 50	22	45	170 to 241
Vickers' 50-ton carbon steel. Normalized at 825° C.	0·45 to 0·55	0·20 to 0·85	0·15 to 0·25	0·035 (max.)	0·035 (max.)	20	40 to 50	20	55	163 to 212
Ditto. Oil-hardened at 825° C. and tempered at 575° C.	Nickel 0·5	,,	,,	,,	,,	28	45 to 60	18	46	197 to 285
Firth's 30-ton carbon steel. Normalized at 850° C.	0·28 to 0·40	0·45 to 0·80	0·30	0·06 (max.)	0·06 (max.)	15 to 20	30 to 40	25	50	—
Firths' 40-ton carbon steel. Normalized at 850° C.	0·45 to 0·55	0·50 to 0·70	0·30	0·06 (max.)	0·06 (max.)	20 to 25	40 to 50	22	40	—
Allen's 40-ton carbon steel. As rolled ..	Corresponds with "E.S.C. 35"					22 to 25	35 to 40	28 to 32	55 to 65	150 to 160
Ditto. Oil-hardened at 850° C. Reheated to 500° C. and cooled off in air.						24 to 28	40 to 45	28 to 32	60 to 70	150 to 160
Jonas, Colver and Co.'s medium carbon steel for crank-shafts; front axles, aero. cylinders, etc. Untreated.	—	—	—	—	—	24	42	25	40	187
Ditto. Heat-treated to maker's instructions	—	—	—	—	—	30	45	25	50	202

Automobile 40-ton Steel.

The medium carbon steels given upon the preceding pages to the E.S.C. Specifications, and also those shown in Table LVIII., are suitable in most cases for drop forgings and stampings of an inexpensive nature, for automobile work. It is also used for aeroplane engine cylinder and crank-case forgings.

The following analysis and mechanical test results refer to the material employed* for the Daimler motor-bus front axles and connecting rods. The steel employed was a medium carbon one, obtained from Swedish iron of special purity, and was stiff but ductile after heat treatment.

The chemical composition was as follows:

Carbon	0·28 to 0·33 per cent.
Silicon	0·05 to 0·10 ,,
Manganese	0·50 to 0·65 ,,
Sulphur	0·03 to 0·04 ,,
Phosphorus...	trace to 0·40 ,,

The tensile test results after treatment were as follows:

Elastic limit	28 to 32 tons per square inch.
Tensile strength	40 to 46 ,, ,,
Elongation in 2 inches ..	20 to 25 per cent
Reduction of area	45 to 35 ,,
Impact test	60 to 70 foot-pounds.

Figs. 164 and 165 show the structure of the above steel before and after heat treatment respectively.

High-Carbon Steels.

Steel containing 0·8 per cent. of carbon and above possesses a fine granular texture, is very hard, even in the rolled or untreated state, and when suitably heat-treated can be made extremely hard; these steels are chiefly employed for tools, metals, stone, and timber-cutting instruments.

In the hardened state this steel is brittle, but gives a high tensile strength, with small elongation.

Most tool and cast steels belong to this class, for when quenched from about a cherry-red heat (from 760° to 850° C.) in oil or water, and then tempered (or reheated to a definite

* "Materials for Motor-Bus Construction," *Engineering*, January 17, 1913.

temperature below the hardening heat) they are capable of yielding a very wide range of hardnesses and strengths, and suitable for a variety of purposes.

FIG. 164.—FRONT AXLE STEEL BEFORE HEAT TREATMENT. ETCHED WITH 5 PER CENT. NITRIC ACID IN ALCOHOL. × 160.

FIG. 165.—FRONT AXLE STEEL, AFTER HEAT TREATMENT. ETCHED WITH 5 PER CENT. NITRIC ACID IN ALCOHOL. × 160.

The following table shows the effect of the carbon content in high-carbon steels upon the mechanical strength properties, and also the effect of hardening upon these properties:

TABLE LIX.

STRENGTHS OF HIGH-CARBON STEELS.* (Lebasteur.)

Percentage of Carbon.	*Original State.*			*Hardened in Oil.*			*Hardened in Water.*		
	Elastic Limit, Tons per Sq. Inch.	Tensile Strength, Tons per Sq. Inch.	Elongation per Cent. on 8 Inches	Elastic Limit, Tons per Sq. Inch.	Tensile Strength, Tons per Sq. Inch.	Elongation per Cent. on 8 Inches.	Elastic Limit, Tons per Sq. Inch.	Tensile Strength, Tons per Sq. Inch.	Elongation per Cent. on 8 Inches.
0·490	14·61	30·48	24·8	28·32	44·77	12·0	30·48	49·53	2·5
0·709	19·56	43·31	10·0	43·69	68·00	4·0	Broke	in tem	pering.
0·875	20·83	44·39	8·4	57·47	67·31	1·0		,,	
1·050	25·08	54·61	5·2	Broke	in tem	pering.		,,	

The effect of increased *manganese* content up to about 2 per cent. is to increase the tensile strength and diminish the elongation; it appears to have the same effect as carbon. It also facilitates melting and forging of carbon steel.

The hardness of high-carbon steel in the untreated state varies from about 180 to 280 on the Brinell scale. When hardened right out in oil or water the hardness varies from about 400 to 600. For any other temper, the hardness will be approximately proportional to the degree of tempering.

Carbon steel for tools is employed commercially in about six different grades or "tempers," corresponding to the carbon content.

Table LX.† on p. 335 affords particulars of typical carbon tool steels of different tempers, or hardnesses, with the corresponding carbon contents, forging, annealing, and hardening temperatures.

It will be observed that the effect of increased carbon is to lower the annealing and hardening temperatures; this effect has already been pointed out.‡

The term "straight carbon" steel is often employed to carbon tool steel.

* The test pieces were 0·8 inch in diameter and 8 inches between gauge points.

† Tool steels manufactured by Messrs. G. P. Wall (Sheffield).

‡ See p. 269.

TABLE LX.

PROPERTIES OF TOOL STEELS.

Grade of Steel.	*Carbon per Cent.*	*Temperatures Recommended.*			*Remarks.*
		Forging.	*Annealing.*	*Hardening.*	
No. 1 Temper	1·5	800° C.	720° C.	760° C.	Not weldable. Suitable for special turning and planing tools.
No. 2 Temper	1·25	825° C.	720° C.	760° C.	Not weldable. Suitable for machining tools, twist drills, and small culters.
No. 3 Temper	1·125	850° C.	720° C.	760° C.	Weldable with great care. Suitable for large turning tools, culters, taps, punches, dies reamers, etc.
No. 4 Temper	1·0	875° C.	720° C.	760° C.	Weldable with care. For hot setts, large punches, large taps, cold chisels.
No. 5 Temper	0·875	900° C.	750° C.	785° C.	Weldable. For chisels, setts, dies, smiths' tools, large shear blades, masons' tools, etc.
No. 6 Temper	0·75	950° C.	770° C.	800° C.	Easily weldable. For hammers, general dies, and miners' drills.

The chemical composition of a typical carbon tool steel is as follows:

Carbon	1·05 per cent.
Silicon	0·20 ,,
Manganese	0·35 ,,
Phosphorus	0·018 ,,
Sulphur	0·015 ,,

The effect of sulphur in any appreciable quantity is to render the steel "red short," whilst phosphorus causes "cold shortness."

Both silicon and manganese, up to about 0·5 per cent. tend to improve the melting and forging qualities of tool steel.

The processes of hardening and tempering are considered in Chapter VIII.

It should be pointed out that the term "tool steel" in cludes also alloy carbon steels, such as tungsten, cobaltchrom, air-hardening, self-hardening, and high-speed tool steels.

Steel Castings.

Castings can be made in steel similar to those of cast iron, but of at least twice the tensile strength; these castings are now employed in place of cast-iron castings and steel forgings, but special precautions are necessary in order to ensure sound material.

Steel melts at about 2000° C., whilst cast iron melts at about 1500° C., so that steel castings have a much higher contraction; it is usual to allow about $\frac{3}{16}$ inch per foot contraction for steel castings.

The greater contraction gives rise to severe internal stresses, but these may be obviated by judiciously employing other ingredients, such as silicon, aluminium, etc., and by properly annealing the castings after cooling.

Sir Joseph Whitworth employed a process for subjecting the steel during casting to hydraulic pressure; such fluid compressed steel is remarkably sound and strong.

A marked improvement in the manufacture of steel castings for automobile work has been made by the employment of electric furnaces for melting the steel, as the heat can be regulated much better, and there are no products of combustion present.

In the Stassano* electric furnace the steel is melted in a closed crucible by means of an electric arc flame, which is directed downwards upon the metal through the slag; in this way the slag is always hotter than the metal, and the sulphur,

* Fig. 223.

phosphorus, and other impurities are absorbed by the slag. The furnace can be rotated by an electric motor, so that the metal can be stirred and uniformly mixed.

There appear to be two principal types of steel casting used in high-class engineering work—namely:

1. A soft mild casting capable of being forged, with a tensile strength of about 26 to 28 tons per square inch, and from 24 to 28 per cent. elongation.

2. A casting giving a tensile strength of about 40 tons per square inch, with a 15 per cent. elongation.

Composition.—The amount of carbon varies from 0·25 to 1·0 per cent., and of manganese from 0·3 to 0·7 per cent. The effect of increased silicon up to 0·5 per cent., and manganese up to about 0·6 per cent., is to increase the strength but to reduce the ductility.

The composition of a typical good steel casting is as follows:

Carbon	0·27 to 0·30 per cent.
Manganese	0·70 to 0·85 ,,
Silicon	0·3 to 0·4 ,,
Sulphur	not more than 0·04 per cent.
Phosphorus	,, ,, 0·04 ,,

The effects of annealing and oil-toughening are important: annealing relieves any internal strains and also improves the strength and ductility, as the figures in Table LXI. show. Annealing at a dull red heat (that is, at about 900° C.) should continue for at least twenty-four hours.

TABLE LXI.

EFFECT OF ANNEALING AND HARDENING STEEL CASTINGS.*

As Cast.		*Annealed.*		*Hardened and again Annealed.*	
Tensile Strength, Tons per Square Inch.	*Elongation per Cent.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*
24	1 to 5	27 to 30	3 to 8	27 to 36	12 to 20

* Considière, "L'Emploi du Fer."

TABLE LXII.

EFFECT OF CARBON, SILICON, AND MANGANESE, UPON THE STRENGTH AND DUCTILITY OF STEEL CASTINGS. (Foster.)*

Composition per Cent.			*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. on 1·75 Inches.*	*Reduction of Area per Cent.*
Carbon.	*Silicon.*	*Manganese.*			
0·30	0·22	0·63	31·0	24·0	43·8
0·35	0·23	0·61	33·0	22·2	41·0
0·50	0·40	0·66	45·2	5·0	6·3
0·77	0·46	0·67	39·8	1·9	3·3
0·96	0·62	0·64	35·6	1·0	1·8

TABLE LXIII.

PROPERTIES OF STEEL CASTINGS. (Unwin.)

Type.	*Yield Point, or Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. on 2 inches.*
Soft steel castings ..	12	27	22
Medium ,, ..	14	31	18
Hard ,, ..	17	38	15

Note.—The values given represent the minimum limits which may be specified in practice.

Steel castings are widely employed in shipbuilding and general engineering work, and are often more convenient and cheaper to make than steel forgings. In automobile and aircraft work these castings are employed for brackets, covers, spanners, pulleys, complicated parts difficult to forge or machine to shape, etc. Fig. 165A shows a few typical examples of automobile steel castings.†

The following is an abstract from the "Specifications of Steel Castings" of the American Society for Testing Materials:

* Proc. Inst. of Civil Engineers, vol. xc., p. 365.

† The Braintree Casting Co.

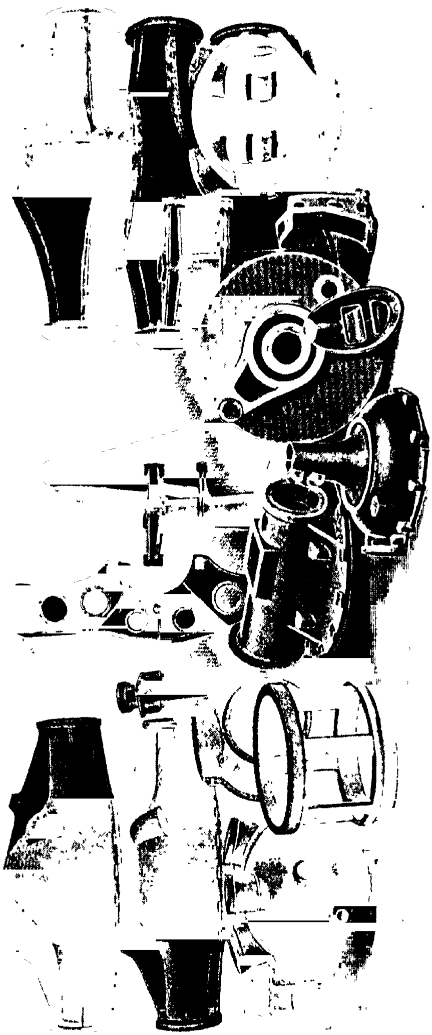


FIG. 165A.—TYPICAL EXAMPLES OF STEEL CASTINGS.

These specifications cover two classes of castings—namely:

CLASS A.—Ordinary castings, where no physical requirements are specified.

CLASS B.—Those for which the requirements are specified. There are three grades in Class B—viz., Hard, Medium, and Soft.

Chemical Composition:

Class A: Carbon, not over 0·3 per cent.; phosphorus, not over 0·06 per cent.

Class B: Sulphur and phosphorus each not over 0·05 per cent.

Physical Properties (Class B):

TABLE LXIV.

Type.	*Yield Point, Pounds per Square Inch.*	*Tensile Strength, Pounds per Square Inch.*	*Elongation per Cent. in 2 inches.*	*Reduction of Area per Cent.*
Hard ..	36,000	80,000	15	20
Medium ..	31,500	70,000	18	25
Soft ..	27,000	60,000	22	30

Bend Tests.—The test specimens for soft castings shall bend cold through 120°, and for medium castings through 90°, around a 1-inch pin, without cracking on the outside of the bent portion. Hard castings shall not be subject to bend-test requirements.

Heat Treatment.—Class A castings need not be annealed unless otherwise specified. Class B castings shall be annealed, which consists in allowing the castings to become cold, and then uniformly reheating them to the proper temperature to refine the grain, and allowing them to cool uniformly and slowly.

Percussion Test.—The casting is suspended by chains and hammered all over by a hammer of a weight approved by the purchaser. If cracks, flaws, or weaknesses appear after such treatment the casting will be rejected.

Aircraft and Automobile Castings.

It is usual to specify steel castings to conform with the Engineering Standards Committee's Report, No. 30—namely, "Steel Castings for Marine Purposes"—in the absence of later standardization.

The tests which the castings must fulfil correspond to those of Grade B in this Report, which specifies a tensile strength of not less than 26 tons per square inch with a minimum elonga tion of 20 per cent.

The usual bending test specified is for a 1 inch square bar to be cast on each casting, or separately; this bar should be capable of being bent to an angle of 120° without signs of flaw, or cracks.

The steel castings used for motor-bus work, and made by the Daimler Co.,* were made from hæmatite pig iron melted in a special furnace and then blown, so that no additional sulphur was taken up as in the case of the ordinary methods where the metal is melted in one cupola and then transferred to the converters before being blown.

The castings were normalized after fettling by heating up to a temperature above the recalescent point and allowing to cool slowly.

Oil-Quenching.

For certain purposes the castings are "oil-toughened" by heating up to the same temperature and quenching in oil.

The effect of oil-quenching is to refine the grain, and to raise the tensile strength by a few tons per square inch, and to increase the elongation.

The impact test value before oil-toughening is about 10 to 12 foot-pounds, whereas after the process it is increased to from 25 to 45 foot-pounds according to the size of the casting.

The following is given as an average analysis of the steel castings made by Messrs. Daimler:

Carbon	0·20 to 0·24 per cent.
Silicon	0·18 to 0·22 ,,
Sulphur	0·015 to 0·030 ,,
Phosphorus	0·024 to 0·04 ,,
Manganese	0·60 to 0·70 ,,

The mechanical test results corresponding are:

Elastic limit	20·5 tons per square inch.
Tensile strength	30 ,, ,,
Elongation in 2 inches	22 to 25 per cent.
Reduction of area	35 to 40 ,,

* "Materials for Motor-Bus Construction," *Engineering*, January 17, 1913.

Figs. 166 and 167 show typical micrographs of the steel structure of the above castings before and after annealing;

FIG. 166.—AUTOMOBILE STEEL CASTING BEFORE HEAT TREATMENT. ETCHED WITH 5 PER CENT. NITRIC ACID IN ALCOHOL. × 160.

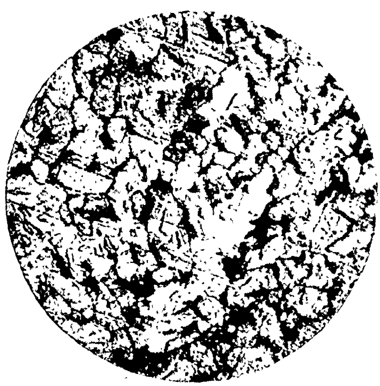


FIG. 167.—AUTOMOBILE STEEL CASTING AFTER HEAT TREATMENT. ETCHED WITH 5 PER CENT. NITRIC ACID IN ALCOHOL. × 160.

the effect of the latter process upon the granular structure is marked.

CHAPTER VI

ALLOY OR SPECIAL STEELS

The term "alloy" steel is rather a misnomer, for there is no so-called carbon steel which is entirely free from elements other than carbon.

Carbon steels invariably contain small percentages of silicon, manganese, sulphur, and phosphorus, and it has been found that the presence of small quantities of silicon are a distinct advantage; and the same applies to manganese. Both of these elements are usually kept down below 1 per cent. in carbon steels.

When other elements, such as nickel, chromium, vanadium, or tungsten, are introduced, even in small amounts, the properties of the steels formed are affected in a marked manner; similarly, when either the manganese or silicon content is noticeably increased the properties of the steel are altered.

These steels are usually termed "alloy" or "special" steels, and they possess peculiar strength and fatigue-resisting qualities, which render them very suitable for aircraft and automobile work.

In aircraft work, where maximum strength for weight is of primary importance, alloy steels have almost entirely supplanted the older mild steels.

For automobile work, where the parts are subjected to repeated and reversed stresses due to road shocks, torque variations, and similar causes, alloy steels are now widely employed.

These steels are more expensive than carbon steels, more difficult to work, and require, as a rule, considerably more care in the heat treatment necessary for the development of their special properties.

In certain instances, such as in the case of malleable iron and steel castings, carbon-steel stampings and forgings, and in the case of parts requiring a very hard skin after case-hardening, iron and carbon steels are found to possess certain advantages in the matter of cost, convenience, and treatment, and are therefore widely used for their particular purposes.

The properties of a carbon steel of given carbon content can be varied over a very wide range by the addition of small amounts of certain elements, such as nickel, chromium, vanadium, or tungsten, which affect the nature of the carbon and iron in the structure of the resulting metal.

The following results show the effect of the above elements upon the mechanical properties of steel of 0·30 per cent. carbon content in the untreated condition:

TABLE LXV.

EFFECT OF DIFFERENT ELEMENTS UPON THE PROPERTIES OF 0·30 PER CENT. CARBON STEEL (UNTREATED).

Other Elements Present.	*Yield Point, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation on 2 Inches, per Cent.*	*Reduction of Area per Cent.*
Plain 0·30 per cent. carbon steel	17	20	30	55
With 3 per cent. nickel ..	24	42	24	45
With 3·5 per cent. nickel and 0·75 per cent. chromium	43	52	17	45
With 1·3 per cent. chromium and 0·18 per cent. vanadium	44	55	16	45
With 12·0 per cent. chromium	38	48	20	47

By heat-treating these steels their mechanical properties can be varied over a very wide range as compared with plain carbon steels.

In general, as the percentage of carbon in alloy steels increases, so does the yield point and tensile strength increase and the elongation decrease.

The maximum percentages of carbon occur in high-speed

tool steels, in which from 0·8 to about 1·8 per cent. of carbon occurs.

Almost all of the modern alloy steels contain below about 0·45 per cent. of carbon, as a reference to Table LXVIII. will show.

Classification of Alloy or Special Steels.

Steels employed in aircraft and automobile work may be classified either according to their compositions and heat treatments or according to the nature of the loads or stresses to which they are particularly suited. In the following considerations the former method will be primarily followed, as it affords a more convenient means of reference.

The second method is of interest from the designer's point of view, and consists in dividing the types of loading which occur in practice into classes, and then allotting to each class all appropriate steels.

There are five principal classes of mechanical actions, each corresponding to distinct conditions of strength and wear occurring in automobile and aircraft work—namely:

(*a*) Simple shear, tension, or compression.

(*b*) Alternating shear, tension, or compression.

(*c*) Sudden blows, shocks, or impacts, causing simple stresses.

(*d*) Pure wearing or abrasive action, with light stresses.

(*e*) Pure wearing or abrasive action, with alternating or impact stresses.

Many other conditions of combined stresses and abrasive actions may, and often do, occur in practice, but the above represents a convenient and representative classification.

In class (*a*), and more especially in cases where weight considerations are secondary to those of convenience and economy of manufacture, the low and medium carbon steels may be employed—for example, for chassis frames, tie-rods, brackets, etc., on automobiles.

Classes (*b*) and (*c*), which occur in aircraft, aero-engine and automobile work, are usually associated with weight

economy conditions, and are frequently unassociated with cheapness considerations; they therefore almost invariably require the highest grades of alloy steels suitably heat-treated, and especially appropriate to their particular purposes—for example, the nickel, nickel-chrome, and chrome-vanadium steels are very suitable for these two classes.

Class (*d*) demands, as a rule, only a good wearing surface material. Cast iron is particularly suitable in many cases, such as for pistons and cylinders, valve-seatings, etc.

Case-hardened mild steel is also appropriate for machined parts where cost and high-core strength are not essential. This material is easy to machine and cheap, and can be given a glass-hard surface by case-hardening. It is employed for small pins, forgings with wearing parts, bolts, nuts, forks, and eyes, and almost all lightly stressed members subject to abrasive action.

Class (*e*) combines the requirements of classes (*b*), (*c*), and (*d*), and necessitates the use either of a case-hardening alloy steel, such as low nickel or nickel-chrome steel, or of a hardened alloy or carbon steel, such as a quenched or quenched and tempered alloy steel or high carbon steel. Air-hardening nickel-chrome and tungsten-steels are suitable for this purpose, and in cases where high simple stresses occur combined with abrasive action.

Ball-bearing components are examples of this latter type of " high simple stress with wear " class.

Effect of Heat Treatment.

It is possible to employ the same alloy or carbon steel for different classes of work by simply varying the heat-treatment. In particular, the alloy steels are frequently employed in a variety of degrees of hardness and strength, obtained purely by heat-treatment processes, for a variety of different purposes. As an example might be quoted a typical nickel-chrome, oil-hardening steel* for which the following results are obtained by heat-treating in the manner specified:

* Manufactured by S. Osborne and Co., Sheffield.

TABLE LXVI.

VARIATION OF THE MECHANICAL PROPERTIES OF NICKEL-CHROME STEEL BY HEAT TREATMENT.

Condition.	*Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation on 2 Inches, per Cent.*	*Reduction of Area per Cent.*	*Brinell Hardness.*
1. Annealed	37	45	45	60	212
2. Oil-quenched from 835° C. and tempered to 600° C. ..	62	66	19	60	302
3. Oil-quenched from 835° C. and tempered to 400° C. ..	78	89	12	45	387
4. Oil-quenched from 835° C. and tempered to 200° C. ..	97	101	10	40	477

This steel in the annealed condition would be suitable for bolts, studs, and small parts subject to vibration, whilst in the heat-treated condition would be appropriate for crank-shafts, connecting-rods, torque members, etc.

Figs. 168, 169, and 170 show in a very convenient graphical manner how the tempering process affects the properties of nickel-chrome, air-hardening nickel-chrome, and chrome-vanadium steels, respectively, after quenching from the temperatures stated upon the diagrams.

Fig. 168 refers to Messrs. Allen's* nickel-chrome steel (N.C.S.) which is suitable for parts subjected to shocks, or impacts and alternating stresses, such as crank-shafts, gear-shafts, connecting-rods, axles, pins, links, etc.

Fig. 169 refers to a chrome-vanadium steel also made by Messrs. Allen, and which is much used for automobile work. It is easier to machine and stamp than nickel-chrome steel, but can be employed for the same purposes.

Fig. 170 represents the properties of an air-hardening nickel-chrome steel† containing [0·25 to 0·35] per cent. carbon, 0·45

* Messrs. Edgar Allen and Co., Sheffield.

† Manufactured by Messrs. Vickers, Ltd., Sheffield.

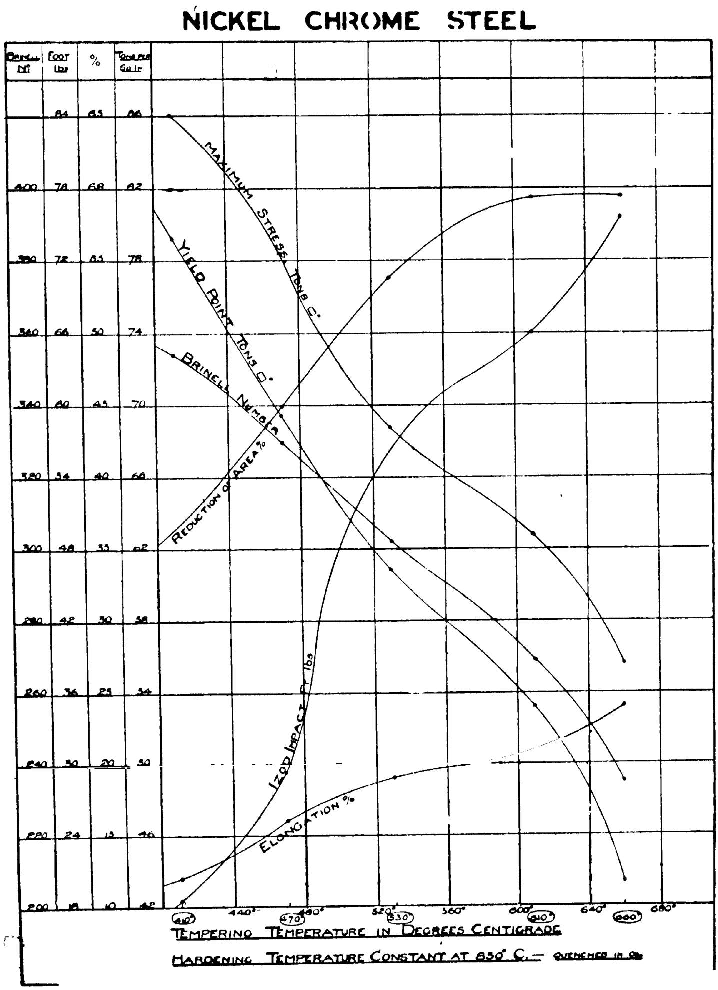


Fig. 168.—Mechanical Properties of Nickel-Chrome Steel for Different Tempering Temperatures.

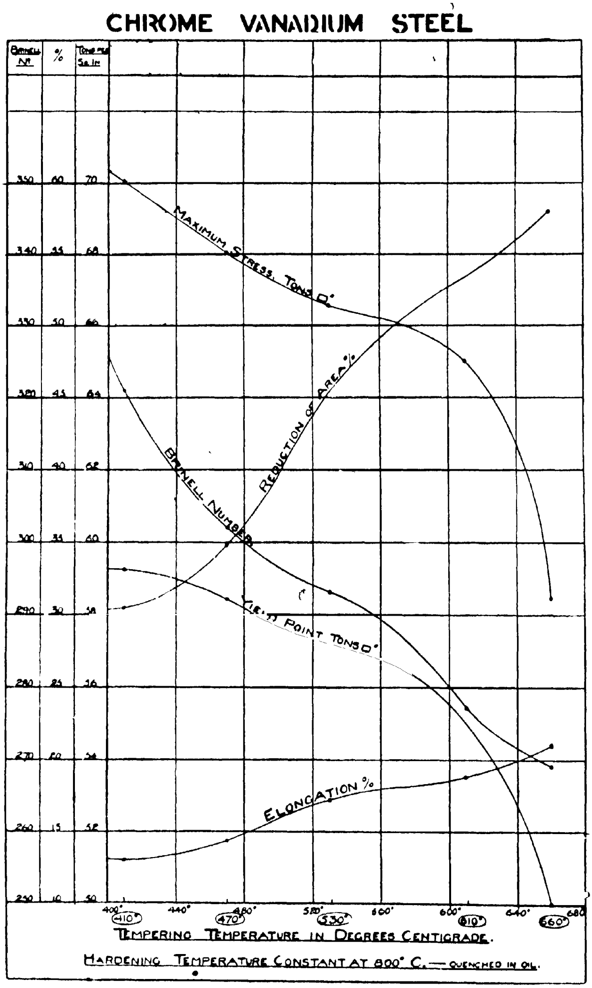


FIG. 169.—MECHANICAL PROPERTIES OF CHROME-VANADIUM STEEL FOR DIFFERENT TEMPERING TEMPERATURES.

per cent. manganese, [3·50 to 4·25] per cent. nickel, and [1·0 to 1·5] per cent. chromium.

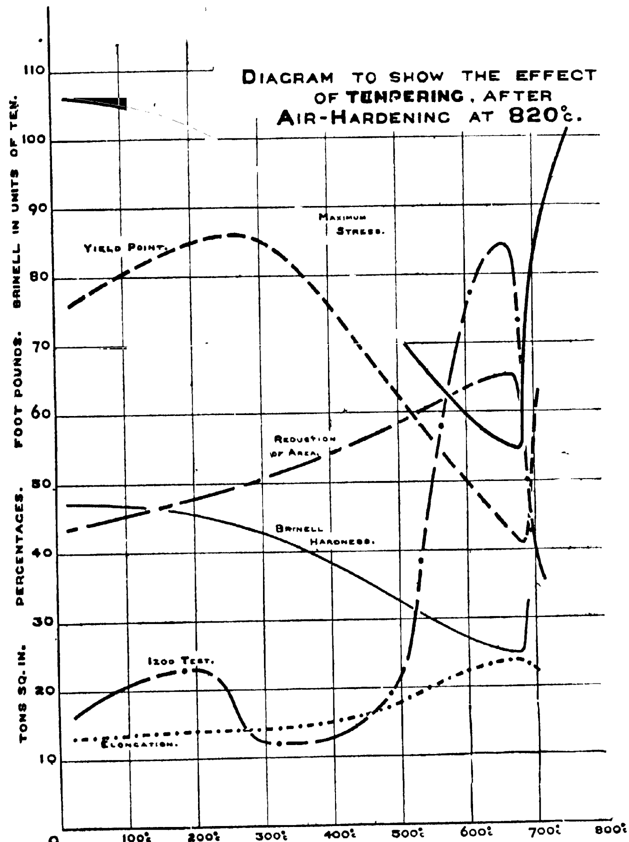


FIG. 170.—MECHANICAL PROPERTIES OF AIR-HARDENING (NICKEL-CHROME) STEEL FOR VARIOUS TEMPERING TEMPERATURES.

Referring again to Fig. 168, it will be seen that, as the temperature of tempering increases, the yield point, tensile strength, and hardness decrease, whilst the percentage elongation and impact value progressively increase.

In the case of the air-hardening nickel-chrome steel shown in Fig. 170, the Brinell hardness for the air-hardened state from 820° C. is 426, whereas when reheated to 650° C., it is about 250. The corresponding values of the tensile strength are 107 and 56 tons per square inch respectively.

Classification according to Compositions.

Reverting once again to the question of classifying alloy steels* according to their constituents, the method proposed by Dr. Guillet† for French automobile steels divides these into six different classes, as follows:

1. Steels with low carbon and low nickel contents (carbon, from 0·1 to 0·25 per cent.; nickel, from 1 to 6 per cent.) suitable for parts requiring case-hardening and quenching, and appropriate for shafts, gears, pins, cams, etc.

2. Steels with medium carbon contents and low percentages of nickel (carbon, from 0·25 to 0·40 per cent.; nickel, 1 to 6 per cent.), which require quenching and tempering, and are suitable for shafts, connecting-rods, axles, forgings, etc.

3. Steels with low carbon content and high percentages of nickel (carbon, from 0·1 to 0·2 per cent.; nickel, from 32 to 36 per cent.), suitable for exhaust valves and "non-corrodible" parts.

4. Chrome steels, containing high carbon content and low chromium content (carbon, 1·0 to 1·2 per cent; chromium, 1·0 to 25 per cent.), suitable for bearings.

5. Silicon steels, containing medium carbon and silicon contents (carbon, from 0·3 to 0·7 per cent.; silicon, 0·8 to 2·5 per cent.), suitable for springs.

6. Nickel-chrome steels of medium carbon content (carbon, from 0·25 to 0·45 per cent.; nickel, from 2·5 to 2·7 per cent.; chromium, from 0·275 to 0·6 per cent.), suitable for a variety of automobile parts subject to shock, but requiring a certain degree of hardness.

Since Guillet's classification other types of alloy steels have

* See p. 345.

† *Journal of Iron and Steel Institute*, vol. ii., p. 166.

been developed, which tend rather to extend the number of classes than to alter the existing ones.

The author has adopted the following method of grouping the present alloy steels, based primarily upon their respective compositions, and also upon their applications:

(*A*) **Case-Hardening Alloy Steels,** including 2 per cent. nickel, 3½ per cent. nickel, 5 per cent. nickel, and nickel-chrome steels.

(*B*) **Nickel Steels,** including 3 per cent. nickel up to 6 per cent. nickel, and 25 per cent. nickel steels.

(*C*) **Nickel-Chrome Steels,** including carbon, from 0·15 to 0·35 per cent.; nickel, from 2 to 5 per cent.; and chromium, from 0·3 to 1·5 per cent. (includes air-hardening steels).

(*D*) **Chrome-Vanadium Steels,** including from 0·2 to 0·5 per cent. of carbon, from 1 to 2 per cent. of chromium, and 0·10 to 0·30 per cent. of vanadium.

(*E*) **High Chrome Steels,** or "stainless" steels, containing from 0·3 to 0·50 per cent. of carbon, and from 11 to 14 per cent. of chromium.

(*F*) **Silicon, and Silico-Chromium Steels,** for springs, with carbon, from 0·6 to ·01 per cent.; silicon, from 0·2 to 2·5 per cent.; and chromium, from 0 to 0·8 per cent.

(*G*) **High Manganese Steels,** or "non-magnetic" steels, with from 0·6 to 1·4 per cent. of carbon, and from 11 to 15 per cent. manganese.

(*H*) **Tungsten,** or "high-speed and magnet steels," containing carbon, from 0·6 to 1·8 per cent., and tungsten, from 4 to 15 per cent.

There are many other types of special alloy steels, such as nickel-chrome-vanadium, nickel-vanadium, chrome-tungsten, cobalt-chrome, carbon-vanadium steels, and no doubt many new steels will be discovered in the future which come outside any of these classes. Tool and high-speed steels* are also in a class by themselves.

Table LXVII. shows in convenient form the compositions and applications of the previously mentioned steels in the

* Further reference to the properties of these steels is made upon p. 387.

TABLE LXVII.

Classification of Alloy Steels.

No.	*Type of Steel.*	*Percentage of Carbon.*	*Percentage of Other Elements.*	*Typical Applications.*
A.	Case-hardening, 2 per cent. nickel	0·10 to 0·15	Nickel, 2·0 to 2·5; Silicon, 0·3; Manganese, 0·4	Gears, spindles, pins, levers.
	Case-hardening, 3½ per cent. nickel	0·10 to 0·15	Nickel, 3·0 to 3·75; Silicon, 0·3; Manganese, 0·4	Highly stressed parts subjected to wearing action.
	Case-hardening, 5 per cent. nickel	0·10 to 0·15	Nickel, 4·75 to 5·75; Silicon, 0·2; Manganese, 0·4	Highly stressed parts subjected to shock and fatigue effects with wearing action.
	Case-hardening, nickel-chrome ..	0·10 to 0·15	Nickel, 3·0 to 4·0; Ditto.	Ditto.
B.	Nickel steel, 3 per cent.	0·25 to 0·35	Nickel, 2·75 to 3·50; Silicon, 0·3; Manganese, 0·5	Crank-shafts, axles, connecting-rods, drop forgings, shafts, etc.
	Nickel steel, 25 per cent.	0·25 to 0·3	Nickel, 25·0; Manganese, 0·3	Non-magnetic and non-corrodible valves.
C.	Nickel-chrome steel, mild.. ..	0·15 to 0·25	Nickel, 3·5; Chromium, 0·6; Silicon, 0·35; Manganese, 0·45	Crank-shafts of lorries, axles, etc.
	Nickel-chrome steel, medium ..	0·25 to 0·35	Nickel, 3·6; Chromium, 0·6; Silicon, 0·35; Manganese, 0·45	Highly stressed parts subject to shock, tubes, plates, axles, connecting-rods, propeller shafts.
	Nickel-chrome steel, high tensile ..	0·30 to 0·40	Nickel, 3·6; Chromium, 0·6; Silicon, 0·35; Manganese, 0·45	Crank-shafts and connecting-rods of aero-engines, etc.
	Nickel-chrome steel, self-hardening	0·25 to 0·35	Nickel, 3·8; Chromium, 1·25; Silicon, 0·35; Manganese, 0·45	Aero-parts, turnbuckles, gears, connecting-rods, long shafts, very highly stressed light parts.
D.	Chrome-vanadium steel	0·35 to 0·45	Chromium, 1·2 to 1·4; Vanadium, 0·16 to 0·20; Silicon, 0·3; Manganese, 0·7	Crank-shafts, gear-shafts, connecting-rods, brake rods, tie rods, stampings, etc.
E.	Stainless chromium steel	0·3 to 0·5	Chromium, 11·0 to 14·0; Silicon, 0·3; Manganese, 0·2 to 0·5	Valves, aircraft wires and rods, seaplane fittings and stressed parts, cutlery, etc.
F.	Silicon-chromium steel and silicon steel	0·5 to 0·6	Silicon, 0·95 to 1·15; Manganese, 0·3 to 0·4; Chromium, 0·6 to 0·8	Springs for valves, leaf springs, and for general spring purposes.
G.	Manganese steel	1·2	Manganese, 11·0 to 15·0	Non-magnetic, aero-sheet-metal work,

TABLE LXVIII.—THE PROPER

Material.	Heat Treatment	Chemical Analysis (Composition per Cent.).	
		Carbon.	Silicon.
Vickers' 3 per cent. nickel steel	Normalized at 840° C.	0·25 to 0·37	0·35 (max.)
Ditto	Oil-hardened at 840° C., and tempered at 550° C.	,,	,,
Firth's 3 per cent. nickel steel	Oil-hardened at 850° C., and tempered at 630° C.	0·30 to 0·40	0·30 (max.)
Allen's 3 per cent. nickel steel	Oil-quenched at 850° C., and tempered at 500° C.	—	—
Vickers' mild nickel-chrome steel	Oil-hardened at 830° C., and tempered at 500° to 600° C. (preferably 600° C.)	0·18 to 0·25	0·35 (max.)
Vickers' medium nickel-chrome steel	Oil-hardened at 825° C., and tempered at 560° to 620° C., followed by oil or water quenching	0·25 to 0·35	0·35 (max.)
Vickers' hard nickel-chrome steel	Oil-hardened at 820° C., and tempered at 550° to 600° C., followed by oil or water quenching	0·30 to 0·40	0·35 (max.)
Firth's nickel-chrome steel	Oil-hardened at 830° C., and tempered at 600° C., followed by quenching	0·28 to 0·34	0·30 (max.)
Firth's air-hardening nickel-chrome steel	Air-hardened at 810° C. [May also be tempered at 250° C. to improve the elongation for same tensile strength]	0·25 to 0·32	0·30 (max.)
Vickers' air-hardening nickel-chrome steel	Air-hardening and tempered between 560° and 640° C.	0·25 to 0·35	0·35 (max.)
Ditto	Air-hardened at 820° C., tempered at 200° C. and quenched	,,	,,
Firth's chrome-vanadium steel	Oil-hardened at 850° C., tempered at 650° C.	0·37 to 0·42	0·30 (max.)
Firth's stainless chrome steel	Oil-hardened at 900° C., tempered at 600° C.	0·30 to 0·50	0·30 (max.)
High nickel steel (non-magnetic)	Quenched	0·25	—
Manganese steel (non-magnetic)	Quenched from 900° to 950° C. ..	1·0 to 1·3	0·30 to 0·40
Tungsten (magnet) steel	Quenched	0·6 to 0·8	0·30 (max.)
Carbon spring steel ..	Hardened and tempered	0·90 to 0·10	0·15 to 0·25
Silicon steel (spring) ..	Annealed	0·50	1·75
Ditto	Heat-treated	,,	,,
Chrome steel (Vickers' spring steel)	Normalized. Spring plates, ⅜ inch thick, oil-hardened at 820° C., and tempered from 450° to 500° C.	0·55 to 0·65	0·20 to 0·50
Ditto	—	,,	,,

Chemical Analysis (Composition per Cent.).				*Mechanical Properties.*					
Manganese.	*Nickel.*	*Chromium.*	*Vanadium.*	*Yield Point (Tons per Square Inch).*	*Tensile Strength (Tons per Square Inch).*	*Percentage Elongation on 2 Inches.*	*Percentage Reduction of Area.*	*Izod Impact Test, Foot-Pounds.*	*Brinell Hardness No.*
0·35 to 0·75	2·75 to 3·75	0·30 (max.)	—	20	35 to 50	24	45	—	152 to 229
,,	,,	,,	—	32	45 to 60	22	50	35	201 to 277
0·50 to 0·80	2·75 to 3·25	—	—	29·2	45 to 55	22	50	40	—
—	—	—	—	45 to 55	55 to 65	20 to 15	55 to 45	—	—
0·25 to 0·55	3·25 to 4·00	0·40 to 0·80	—	40 (min.)	50 to 60	19	55	40	217
0·25 to 0·55	3·25 to 4·00	0·45 to 0·75	—	45 (min.)	55 to 65	18	50	35	240 to 311
0·25 to 0·60	3·25 to 4·00	0·45 to 0·75	—	50 (min.)	60 to 70	17	40	30 to 35	269 to 341
0·45 to 0·70	3·00 to 3·75	0·50 to 1·00	—	40 to 50	55 to 65	20	50	40	—
0·35 to 0·60	4·0 to 4·5	1·00 to 1·50	—	—	90 to 120	16 to 8	20	20 to 10	—
0·35 to 0·55	3·50 to 4·25	1·00 to 1·50	—	45 (min.)	55 to 65	15	45 to 50	35	240 to 311
,,	,,	,,	—	75 (min.)	100 to 125	8	20	8	429 to 555
0·60 to 0·85	—	1·20 to 1·40	0·16 to 0·20	40 to 50	55 to 65	18	50	—	—
0·20 to 0·50	—	11·0 to 14·0	—	38 to 45	50 to 60	18	45	40	—
0·30	25·0	—	—	15	40	45	50	—	—
12·0 to 15·0	—	—	—	19·0	35·0	20	50	—	—
0·20 to 0·40	*Tungsten* 5·0 to 6·0	—	—	—	—	—	—	—	500 to 650
0·25 to 0·50	*Copper* 0·30 to 0·05	—	—	25 to 30	40 to 50	16 to 20	—	—	—
0·65	—	—	—	—	30 to 40	25 to 20	—	—	—
,,	—	—	—	—	50 to 90	15 to 5	35 to 30	—	—
0·50 to 0·80	—	0·45 to 0·70	—	30 (min.)	55 to 65	15 (min.)	—	—	235 to 277
,,	—	,,	—	75 (min.)	90 to 100	7 (min.)	—	—	418 to 477

TABLE LXIX.

Chemical and Physical Properties of Typical Alloy Case Hardening Steels.

Material and Treatment.	*Chemical Analysis. (Composition per Cent.)*					*Mechanical Properties.*					
	Carbon.	*Silicon.*	*Manganese.*	*Nickel.*	*Chromium.*	*Yield Point (Tons per Square Inch).*	*Tensile Strength (Tons per Square Inch).*	*Elongation on 2 Inches, per Cent.*	*Reduction of Area per Cent.*	*Izod Impact Test, Foot-Pounds.*	*Brinell Hardness No.*
Vickers' 2 per cent. nickel C.H. steel. Normalized at 870° C.	0·10 to 0·15	0·30 (max.)	0·25 to 0·60	2·00 to 2·500	—	14	25 to 35	30	55	—	103 to 152
								Core	*tests.*		
Ditto. Normally carbonized to a depth of $\frac{1}{32}$ inch, and water quenched twice, first at 870° C., and secondly at 770° C.	,,	,,	,,	,,	—	21	35 to 45	25	55	50	—
Vickers' 3½ per cent. nickel C.H. steel. Normalized at 850° C.	0·10 to 0·15	0·30 (max.)	0·25 to 0·50	3·00 to 3·75	0·30 (max.)	16	28 to 40	28	55	—	103 to 153
								Core	*tests.*		
Ditto. Normally carbonized to a depth of $\frac{1}{32}$ inch, and water quenched twice, first at 850° C., afterwards at 770° C.	,,	,,	,,	,,	,,	30	40 to 60	15	45	40	—
Vickers' 5 per cent. nickel C.H. steel. Normalized at 820° C.	0·09 to 0·13	0·10 to 0·25	0·10 to 0·25	4·75 to 5·75	0·20 (max.)	17	28 to 40	28	55	—	—
Ditto. Normally carbonized to a depth of $\frac{1}{32}$ inch at 900° to 950° C., then cooled and reheated to 780° C., and water quenched.	,,	,,	,,	,,	,,	40 to 50	50 to 85	25 to 10	40 (min.)	17 to 38	—
Firth's 2 per cent. nickel C.H. steel. Cemented at 900° C., refined at 900° C., water-hardened at 760° C.	0·10 to 0·18	0·30 (max.)	0·30 to 0·60	1·75 to 2·25	— —	—	35 (min.)	25	55	60	—
Firth's 5 per cent. nickel C.H. steel. Cemented at 900° C., refined at 830° C., water-hardened at 760° C.	0·08 to 0·15	0·30 (max.)	0·20 to 0·40	4·75 to 5·25	—	—	45 (min.)	20	50	45	—
Osborne's nickel-chrome C.H. annealed steel.						38	42	28	70	—	196
Ditto. Carbonized 950° C., reheated at 850° C. and quenched in oil, reheated to 780° C. to 800° C. and quenched in water.						79	89	14	40	—	418

order of their classification, but the examples are more or less limited to automobile and aircraft engineering work.

Table LXVIII. gives in more detail the chemical analyses together with the corresponding mechanical strengths of typical aircraft and automobile steels when heat-treated* in the manner specified; the results shown are actual analysis and test figures.

The case-hardening alloy steel results are given in Table LXIX.

At the end of the present chapter will be found in Tables LXXX., LXXXI., LXXXII., and LXXXIII. some useful particulars regarding the application of alloy steels to aircraft and automobile work.

Application and Use of Alloy Steels.

It is not within the scope of the present work to discuss the methods of manufacture of the various materials mentioned, but a few remarks may not be out of place anent the great care that is necessary in the preparation and application of alloy steels.

In the first place, it is necessary during manufacture to obviate all possibility of defects arising in the material before it reaches the rolls; most of the alloy steels are more liable to surface markings, flaws, and blemishes in the early stages of their manufacture. The billets are carefully inspected, and all visible surface flaws are removed by chipping with a pneumatic chisel† made of a special high-speed steel; the large billets are then rough-turned in a lathe before being rolled to the finished size. These processes involve a certain small loss in weight of the material, but amply repay the trouble by eliminating defects which might otherwise tend to cause the rejection of the batch of material through failure to conform to a given specification.

Samples of typical batch materials are taken, analyzed, and

* The subject of heat treatment is considered in Chapter VIII.

† The author is indebted to Messrs. Edgar Allen for the above notes upon their methods for eliminating the possibilities of defects in their steels.

subjected to mechanical tests, in order to check uniformity in composition, heat treatment, and strength.

A certain amount of experience, usually only derived from actual practice, is necessary in the selection of alloy steels and in their subsequent heat treatment. Most of the failures which occur in engineering work can usually be traced back, either to the selection of the wrong material for the purpose or to the incorrect heat treatment. In the latter case, the article may have been carefully designed and manufactured, but either over- or under-heated before quenching, or wrongly tempered.

The use of correct hardening furnaces, tempering baths, and accurately reading pyrometers, together with a strict adherence to the steel manufacturers' instructions, will obviate any such failures.

In utilizing special steels attention should be paid to the size and shape of the articles manufactured from them, for the effect of "mass" * has a marked influence upon the heat-treatment process; for example, small, light, and fragile parts do not require to be heated to such a high temperature, or for so long a time, as heavier and more solid parts of the same material. Again, it is necessary to know the behaviour of the selected steel in forging, rolling, or stamping, since some steels are notably difficult to work and often quite unsuited to the particular class of work.

Case-Hardening Alloy Steels.

Carbon steels containing from 2 to 5 per cent. of nickel, or both nickel and chromium, possess the advantage over ordinary mild steels of a much stronger core after being case-hardened, although the hardness of the carburized layer or skin is not equal to that of carbon steels.

In high-grade automobile and in aircraft work, these alloy steels are replacing carbon steels; but for cheaper and less important work, and in cases where the skin hardness is of primary importance, case-hardening carbon steels are to be preferred.

* See Chapter VIII.

The principal advantage of case-hardening alloy steels lies in the fact of their possessing a tougher core, capable of withstanding reversed stresses and shocks, and of providing lighter parts of equal strength to those made of carbon steel.

As will be seen from the figures given in Table LXIX., it is possible to obtain cores having tensile strengths up to 85 tons per square inch, with a 10 per cent. elongation, whereas the maximum tensile strength in the case of carbon steels is about 40 tons per square inch in the hardened condition.

The following specifications are given by the Engineering Standards Committee for case-hardening nickel steels:

(A) E.S.C. 2 PER CENT. NICKEL CASE-HARDENING STEEL.

Chemical Composition:

Carbon	0·10 to 0·15 per cent.
Silicon	not over 0·3 ,,
Manganese	0·25 to 0·50 ,,
Sulphur	not over 0·05 ,,
Phosphorus	,, 0·05 ,,
Nickel	2·00 to 2·50 ,,

Check Test.—When normalized at 850° to 900° C. this steel shall pass in every particular the following test

Tensile strength	25 to 35 tons per square inch.
Yield ratio	not less than 55 per cent.
Elongation	,, ,, 30 ,,
Reduction of area	,, ,, 55 ,,

The corresponding Brinell hardness number should be approximately 103 to 153.

(B) E.S.C. 5 PER CENT. NICKEL CASE-HARDENING STEEL.

Chemical Composition:

Carbon	not over 0·15 per cent.
Silicon	,, 0·20 ,,
Manganese	,, 0·40 ,,
Sulphur	,, 0·05 ,,
Phosphorus	,, 0·05 ,,
Nickel	4·75 to 5·75 ,,

Check Test.—When normalized at 820° to 860° C. this steel shall pass in every respect the following check test

Tensile breaking strength	25 to 40 tons per square inch.
Yield ratio	not less than 60 per cent.
Elongation	,, ,, 30 ,,
Reduction of area	,, ,, 55 ,,

The corresponding Brinell hardness number should be approximately 103 to 179.

Effect of Heat Treatment upon Properties of C. H. Nickel Steel.

In Table LXX. the results* given were obtained upon specimens of nickel steel, treated in the manner indicated.

The section of the specimen influences its mechanical properties, the smaller sections being relatively the stronger; this

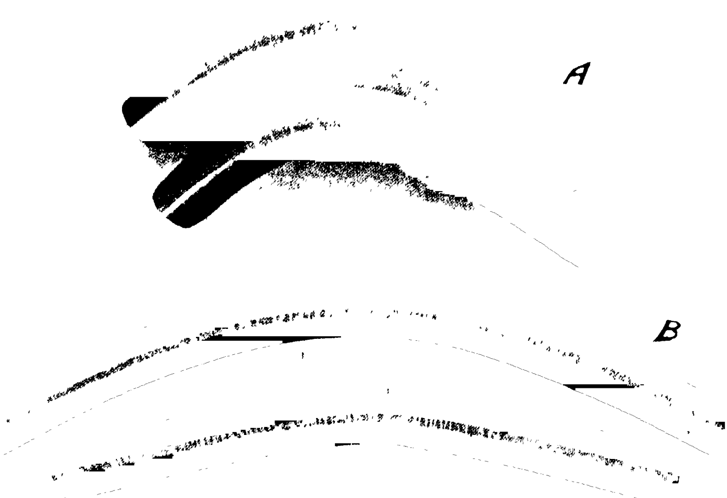


FIG. 171.—CASE-HARDENED NICKEL STEEL BARS. (VICKERS.)

A, Quenched in boiling water
B, Quenched in cold water.

will be seen by comparing the results (3) and (4) in the above table. For small gears, etc., the strengths will correspond to those of (3) and (4).

Nickel Steels.

These may be classified into two classes—namely, the low and the high nickel steels; the former class comprises steels containing from 2 to 5 per cent. of nickel, whilst the latter class includes steels with from 25 to 30 per cent. nickel.

* Messrs. Vickers, Ltd., Sheffield.

TABLE LXX.

PROPERTIES OF CASE-HARDENING NICKEL STEELS WITH DIFFERENT HEAT TREATMENTS.

No.	*Size.*	*Heat Treatment.*	*Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. on 2 Inches.*	*Reduction of Area, per Cent.*
1	--	As softened for machining.	28	33	33	65
2	$\frac{7}{8}$-inch diameter	Case-hardened. Quenched in boiling water from 785° C.	30	36·5	32	70
3	$\frac{7}{8}$-inch diameter	Case-hardened. Quenched in cold water from 785° C.	61·6	67·6	16	57
4	$\frac{5}{8}$-inch diameter	Case-hardened. Quenched in cold water from 785° C	65·6	81·6	15	51

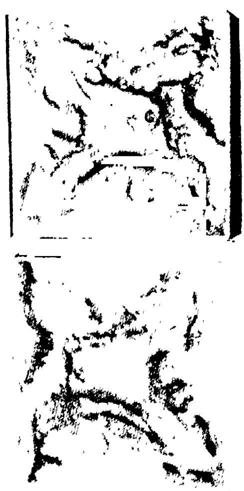


FIG. 172.—FRACTURES OF CASE-HARDENED NICKEL STEEL BARS.

Low Nickel Steels.

Low content nickel steels are now widely used in modern engineering work for members subjected to alternating stress

and shock, for they combine strength and toughness with minimum weight.

TABLE LXXI.

EFFECT OF CARBON CONTENT UPON THE PROPERTIES OF $3\frac{1}{2}$ PER CENT. NICKEL STEEL.

Percentage of Carbon.	*Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Reduction of Area per Cent.*
0·2	21·4	38·0	26	55
0·3	26·8	42·5	22	48
0·4	32·0	49·6	18	40
0·5	37·9	55·8	13	32

FIG. 173.—CASE-HARDENED NICKEL STEEL GEAR WHEELS TESTED TO DESTRUCTION. (VICKERS.)

The type of low nickel steel widely used in automobile work is the 3 to 3½ per cent. nickel steel, containing about 0·30 per cent. of carbon; it has a higher elastic limit than ordinary carbon steel, and a greater fatigue resistance.

A typical analysis, and the corresponding mechanical test results for this type of nickel steel is given in Table. LXVIII.

It will be seen that in the normalized state the tensile strength varies from 35 to 50 tons per square inch, with 24 per cent. elongation and 45 per cent. reduction in area.

When oil hardened at about 840° C. and tempered at 550° C., the tensile strength lies between 45 and 60 tons per square inch, with 22 per cent. elongation, and 50 per cent. reduction in area, so that increased tensile and compressive strengths are obtained without loss of ductility. The hardness after heat-treatment in the above manner varies from 200 to 280, whereas in the normalized state it lies between 150 and 230.

In the heat-treated condition the Izod impact value is about 35 foot-pounds.

The Engineering Standards Committee's Specification for 3 per cent. nickel steel is as follows:

E.S.C 3 PER CENT. NICKEL-STEEL.

Chemical Composition :

Carbon	0·25 to 0·35 per cent.
Silicon	not over 0·30 ,,
Manganese	0·35 to 0.75 ,,
Sulphur	not over 0·04 ,,
Phosphorus	,, 0·04 ,,
Nickel	2·75 to 3·50 ,,

Check Test.—When normalized at 840° to 880° C., this steel shall pass in every particular the following check test.

Tensile breaking strength ..	35 to 45 tons per square inch.
Yield ratio	not less than 55 per cent.
Elongation	,, ,, 24 ,,
Reduction of area	,, ,, 45 ,,

The Brinell hardness number corresponding to the above should be approximately 140 to 202.

The effect of different percentages of nickel upon the tensile strength of very low (0·09 per cent.) carbon steel is shown graphically in Fig. 174, in which diagram the lower curve represents the tensile strengths of slowly cooled specimens,

whilst the upper curve corresponds with the strengths of quenched specimens. The maximum strength of the quenched material is attained when the nickel present lies between about 12 and 16 per cent., and for the annealed specimens, for a nickel content of from 15 to 20 per cent.; these proportions do not, however, correspond with the commercial require-

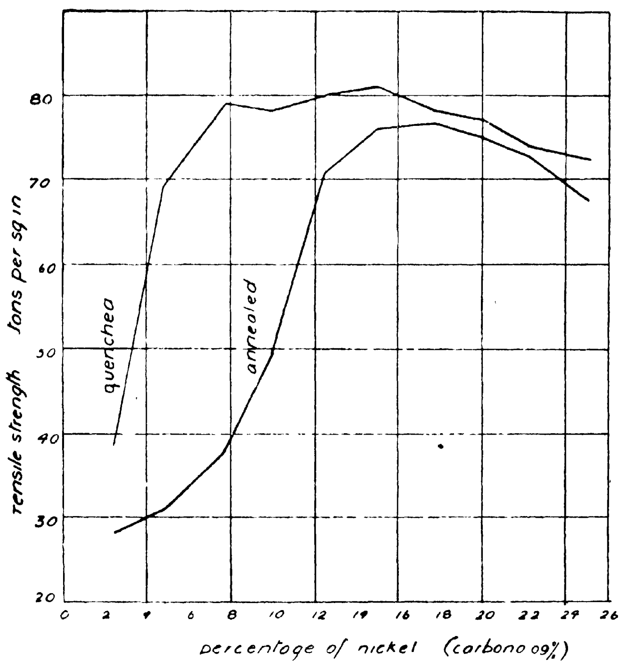


FIG. 174.

ments of hardness, and ductility, etc. The effect of increasing the carbon content up to about 0·9 per cent. of carbon, is to raise the tensile strength, but to lower the ductility qualities after about 0·3 per cent. of carbon is exceeded. The hardness of a 0·7 per cent. nickel steel, of low carbon content (below 0·12 per cent.), even after slow cooling is practically the same as that of a hardened cutting tool and

this material can be case-hardened by carburizing, the surface and allowing to cool slowly, with the result that a very hard skin combined with an extremely tough core is obtained.

Like most other high carbon and alloy steels the mechanical properties of low nickel steels can be widely varied by suitable heat-treatment. The following results show how the mechanical strength is varied by suitable heat treatment for 3 per cent. and 5 per cent. nickel steels, suitable for crankshafts, connecting-rods, axles, etc.:

TABLE LXXII.

PROPERTIES OF NICKEL STEELS.*

Material.	*Heat Treatment.*	*Elastic Limit.*	*Tensile Strength.*	*Elongation per Cent. on 2 Inches.*	*Reduction of Area per Cent.*	*Brinell Hardness.*
3 per cent. nickel steel	Annealed ..	27	39	31	64	170
	Oil quenched at 820° C., tempered at 650° C., and again quenched in oil	47	55	22	57	262
5 per cent. nickel steel	Annealed ..	28	43	19	42	202
	Oil quenched at 820° C., tempered at 650° C., and again quenched in oil	47	65	20	60	302

Compression Strength.

In Table LXXIII. the results† show how the elastic limit in compression is influenced by nickel content in steels of low carbon value.

It will be observed that the compression strain is greatest for small elastic strengths and least for the maximum strengths.

* Samuel Osborne and Co., Ltd., Sheffield.

† Sir R. Hadfield.

TABLE LXXIII.

COMPRESSION STRENGTH OF NICKEL STEELS.

Percentage of Carbon.	*Percentage of Nickel.*	*Elastic Limit in Compression, Tons per Square Inch.*	*Compression Strain. (Shortening by 100-Ton Load per Cent.)*
0·13	0·95	20	49
0·14	1·92	27	47
0·19	3·82	28	41
0·18	5·81	40	37
0·17	7·65	40	33
0·16	9·51	70	3
0·18	11·39	100	1
0·23	13·48	80	1
0·19	19·64	80	3
0·16	24·51	50	16
0·14	29·07	24	41

Other Properties of Nickel Steels.

One valuable feature of nickel steels is the high ratio of the yield point to the tensile strength, which varies from 0·7 to 0·8, whereas in carbon steels it is only from about 0·5 to 0·6; the effect of this high yield ratio is that lower factors of safety (reckoned on the yield point) can be employed.

Nickel steel containing from 3 per cent. to 5 per cent. of nickel can be forged, stamped, and drop-forged, and afterwards heat-treated to attain the desired strength.

The electrical resistance of all nickel steels is high, and it does not appear to vary much with the percentage of nickel. Nickel steel wire containing from 25 to 30 per cent. of nickel has about 48 times the resistance of copper. The low nickel steels (3 to 5 per cent. nickel) have a greater magnetic permeability than wrought iron. The shearing strength of low-nickel steels is about 0·7 of the tensile strength.

The specific gravity of low nickel steels varies from 7·86 to 7·9.

High Nickel Steels.

Nickel steel containing from 25 to 35 per cent. of nickel possesses non-corroding qualities rendering it suitable for parts subjected to rusting action.

When the carbon content is about 0·30 per cent. and the nickel, from $24\frac{1}{2}$ to $27\frac{1}{2}$ per cent., the steel also possesses the non-magnetic property, which renders it useful for parts situated near magnetic compasses, and for similar purposes.

The chemical composition of a typical non-magnetic and "non-corrodible" nickel steel is as follows:

Carbon	0·25 to 0·35 per cent.
Manganese	0·25 to 0·4 ,,
Sulphur	not over 0·04 ,,
Phosphorus	,, 0·04 ,,

The corresponding mechanical strength properties* are as follows:

Nickel	25 per cent.
Yield point	15.
Tensile strength	40.
Percentage elongation	45.
Percentage reduction of area	50.

Quenching does not appear to affect the strength very much, but the material becomes hardened by rolling or hammering.†

This steel possesses a high elongation, and can therefore be bent cold to sharp angles without cracking,

Physical Properties.

High nickel steel has a remarkably low coefficient of expansion, and is there much used for measuring tapes and instruments; the well-known "standards" Invar steel belongs to this class.

Invar steel contains about 0·18 per cent. of carbon, 35·5 per cent. of nickel and 0·42 per cent. of manganese.

It has a coefficient of expansion of 0·000000877 per degree C. The mean value between temperatures of 0° and t° C., (where t does not exceed 200° C.) is given by

$$\alpha=(0{\cdot}877+0{\cdot}00117t)\times 10^{-6} \text{ per } ^\circ\text{ C.}$$

Compared with ordinary steel, Invar steel has $\frac{1}{11{\cdot}5}$, and with brass $\frac{1}{17{\cdot}2}$ of the expansion coefficient.

* In the quenched state.

† See p. 402 for results of tests upon 25 per cent. nickel-steel plates.

Alloys containing 47·5 per cent. of nickel have the same expansion coefficient as glass and platinum.

The following are the values of the expansion coefficient per degree C., for different nickel and carbon steels:

Percentage of Nickel.	*Coefficient of Expansion per Degree C.*
26	0·00001312
28	0·00001131
28·7	0·00001041
30·4	0·00000458
31·4	0·00000340
34·6	0·00000137
35·7	0·00000087
37·3	0·00000356
39·4	0·00000537
44·4	0·00000856
47·5	0·00000870
Ordinary mild steel	0·00001078
Ordinary hard steel	0·00001240

The specific gravity of nickel steels containing from 20 to 40 per cent. of nickel varies from 7·91 to 8·09; 44 per cent. nickel steel has a specific gravity * of 8·12.

High nickel steel is employed for exposed members on sea-planes, and aircraft for exhaust valves, boiler tubes, etc., owing to its non-corrosive effect. It is, however, being steadily supplanted by the high chromium "stainless" steel, which possesses considerably better rust resisting and strength qualities. High nickel steel can be brazed, but cannot be welded in the ordinary manner† by the oxy-acetylene method, although it may be, with great care, by the electrical methods.

Nickel-Chrome Steels.

These steels somewhat resemble the low nickel steels in their properties and applications, but in general they are more expensive, more difficult to work, and they require greater care in forging, stamping, and heat treatment, but they give greater hardnesses and strengths when suitably selected and treated. Tensile strengths up to about 125 tons per square inch can be obtained, with about 10 per cent. elongation, and

* Guillaume. † See Chapter XI. for alloy steel welding processes.

Brinell hardnesses up to 600, in the case of air-hardened nickel-chrome steels.

The compositions and properties of nickel-chrome steels are given in Tables LXVII., LXVIII., and LXIX., and the effects of tempering these steels upon their mechanical properties are shown graphically in Figs. 168 and 170.

The results of heat treatment upon the mechanical properties of this steel are more marked than in the case of low nickel steels, for the tensile strengths and hardnesses are capable of a wider variation by suitable treatment; this point may be illustrated by reference to Table LXVI.

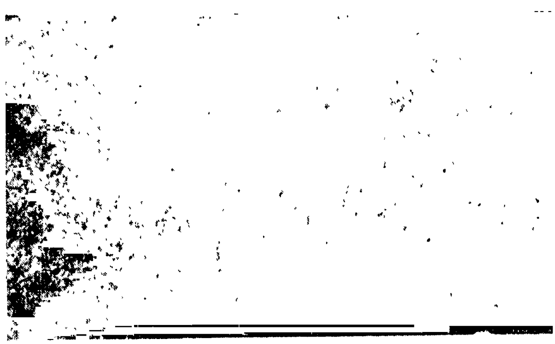


FIG. 175.—NICKEL-CHROME STEEL (HEAT-TREATED CONDITION). × 66.

Fig. 175 shows the micro-structure of heat-treated nickel-chrome steel.

Nickel-chrome steels are usually supplied in three different grades, according to the carbon content, known as the *mild*, *medium*, and *hard* nickel-chrome steels respectively; the compositions of these three types, together with their corresponding mechanical properties, are given in Table LXXXIX. The carbon contents of these steels, in the order named, are from 0·15 to 0·25, from 0·25 to 0·35, and from 0·30 to 0·40 respectively.

It will be seen that the respective tensile strengths when properly heat-treated are, on the average 55, 60, and 65, and the corresponding Brinell hardnesses, 250, 275, and 300.

Mild nickel-chrome steels are easier to manipulate, and can be case-hardened, with rather better results than in the case of low nickel case-hardening steels.

These case-hardening nickel-chrome steels are especially suitable for gears, change-wheels, chain-wheels, cam-shafts, stampings, etc., and possess a very tough fatigue-resisting core, with a glass hard skin.

The following results were obtained with a nickel chrome case-hardening steel:

TABLE LXXIV.

NICKEL-CHROME CASE-HARDENING STEEL.

Condition.	*Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation on 2 Inches per Cent.*	*Reduction of Area per Cent.*	*Brinell Hardness.*
Annealed	38	42	28	70	196
Core, after case-hardening at 950° C. ..	79	89	14	40	418

The medium grade of steel is used for the same purposes as 3 to 5 per cent. nickel steels; it possesses a high elastic limit (from 40 to 45 tons per square inch), great toughness and hardness (Brinell hardness from 250 to 320), good machining qualities, and it can be forged and stamped.

This grade of steel is specially suitable for crank-shafts, connecting-rods, shafts, axles, highly stressed aircraft clips and fittings, etc.

The Engineering Standards Committee's Specifications for nickel-chrome steels are as follows:

(A) E.S.C. 1½ PER CENT. NICKEL-CHROME STEEL.

Chemical Composition:

Carbon	0·25 to 0·35 per cent.
Silicon	not over 0·30 ,,
Manganese	0·35 to 0·60 ,,
Sulphur	not over 0·04 ,,
Phosphorus	,, 0·04 ,,
Nickel	1·25 to 1·75 ,,
Chromium	0·75 to 1·25 ,,

Check Test.—When oil-hardened from 850° C. and tempered at 600° C., this steel shall pass in every particular the following check test:

Tensile breaking strength	not less than	45 tons per square inch.
Yield ratio	,, ,,	70 per cent.
Elongation	,, ,,	15 ,,
Reduction of area	,, ,,	50 ,,

The Brinell hardness number corresponding to the above should be approximately 179.

(B) E.S.C. 3 PER CENT. NICKEL-CHROME STEEL.

Chemical Composition :

Carbon	0·20 to 0·30 per cent.
Silicon	not over 0·30 ,,
Manganese	0·35 to 0·60 ,,
Sulphur	not over 0·04 ,,
Phosphorus	,, 0·04 ,,
Nickel	2·75 to 3·50 ,,
Chromiun	0·45 to 0·75 ,,

Check Test.—When oil-hardened from 820° C. and tempered at 600° C., this steel shall pass in every particular the following check test

Tensile breaking strength	not less than	45 tons per square inch.
Yield ratio	,, ,,	75 per cent.
Elongation	,, ,,	15 ,,
Reduction of area	,, ,,	50 ,,

The Brinell hardness number corresponding to the above should be approximately 179.

Nickel-chrome steel is supplied commercially in billets, bars, forgings, stampings, sheets, tubes, etc.

Air-Hardening Nickel-Chrome Steels.

Reference has already been made* to this class of steel, which is quite distinct from the other high-tensile steels in that it can be hardened by simply heating up to about 800° to 850° C. and allowed to cool in the air, whereas other steels require quenching. Typical micro-photographs of this steel are shown in Figs. 135 and 145 for the tempered and annealed conditions.

This type of steel possess higher nickel and chromium contents and, as a rule, medium or low carbon content.†

The tensile strengths and hardnesses of such steels represent about the maximum that can be obtained with any steels; the average tensile strength varies from 100 to125 tons per square

* See p. 281.

† A typical composition is given in Table LXVIII.

inch, with a yield ratio of about 80 per cent., and elongation of from 8 to 12 per cent. The reduction of area is about 20 per cent. and Brinell hardness 450 to 600.

The Engineering Standards Committee's Specification for air-hardening nickel-chrome steel is as follows:

E.S.C. AIR-HARDENING NICKEL-CHROME STEEL.

Chemical Composition :

Carbon	0·28 to 0·36 per cent.
Silicon	not over 0·30 ,,
Manganese	0·35 to 0·60 ,,
Sulphur	not over 0·04 ,,
Phosphorus	,, 0·04 ,,
Nickel	3·50 to 4·50 ,,
Chromium	1·25 to 1·75 ,,

Check Test.—A test bar of this steel, when air-hardened from 820° C. shall pass in every particular the following test

Tensile breaking strength not less than	100 tons per square inch.
Yield ratio .. .. ,, ,,	75 per cent.
Elongation .. .. .. ,, ,,	5 ,,
Reduction of area .. .. ,, ,,	13 ,,

The Brinell hardness number shall be approximately 418.

The tensile test piece before being air-hardened shall have its parallel portion machined to within 0·02 inch of the finished diameter of the test piece, and this portion shall, after the test piece has been hardened, be reduced to the required diameter by grinding.

The effect of reheating, or tempering upon the mechanical properties of an air-hardening nickel-chrome steel is shown graphically in Fig. 170.

It is usual to finish-machine parts made in this steel, such as gear-wheels, crank-shafts, connecting-rods, turnbuckles, axles, shafts, etc., in the softened condition, with or without making a grinding allowance, and to then air-harden the parts, finishing by grinding where arranged.

It has been found that the degree of air-hardness is dependent upon the rate of cooling and size of the article, although the ordinary cooling-rate when articles are heated to 20° or 30° above the critical point (*i.e.*, about 850°) and allowed to stand in air, is sufficient to attain a tensile strength of at least 100 tons per square inch.

Chrome-Vanadium Steel.

This steel, which is widely used in automobile construction, resembles the low nickel, and nickel-chrome steels in its mechanical properties, but it is easier to stamp and to machine than nickel-chrome steels, and can be used in place of these for such parts as connecting-rods and bolts, selector shafts, brake rods, live and back axles, propeller and lay shafts, crankshafts, etc.

It can be obtained in very sound condition and in the heat-treated state gives tensile strengths varying from 60 to 80 tons per square inch, with from 15 to 10 per cent. elongation on 2 inches and from 45 to 40 per cent. reduction of area. The Brinell hardness varies from 270 to 350 in the hardened state.

The composition of a typical chrome-vanadium steel* is as follows:

Carbon	0·35 to 0·40 per cent.
Manganese	0·60 to 0·80 ,,
Sulphur	0·04 (max.) ,,
Phosphorus	0·04 ,, ,,
Chromium	0·90 to 1·40 ,,
Vanadium	0·16 to 0·20 ,,

Table LXXV. gives some typical test results for this steel.

Chromium and Vanadium Steels.

When either chromium or vanadium is added to mild or medium carbon steel, in small quantities (from 0·1 to 1·0 chromium or from 0·1 to 0·25 vanadium), the tensile strength, hardness, and impact values are appreciably increased.

Table LXXVI.† shows the effect upon crucible steels of small quantities of chromium and vanadium separately, and also when combined.

Mild Vanadium Steel.

The addition of small quantities of vanadium (from 0·10 to 0·25 per cent.) to low carbon steel has the effect of increasing the ductility and shock-resisting qualities, without, how-

* Also see Tables LXVII. and LXVIII.

† Sankey and Kent Smith, Proc. Inst. of Mech. Engrs., 1904.

TABLE LXXV.

Mechanical Test Results for Chrome-Vanadium Steels.

Condition.	*Yield Point, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. on 2 Inches.*	*Reduction of Area per Cent.*	*Brinell Hardness. No.*
(*a*) Annealed	34	41	26	70	192
Oil-quenched at 900° C., then tempered to 600° C.	54	60	22	50	277
(*b*) Oil-quenched at 850° C., then tempered at 650° C. ..	*Yield Ratio.* 75 per cent.	55 to 65	18	50	—
(*c*) As rolled	40 to 50	50 to 60	25 to 20	65 to 55	259 to 269
Oil-quenched at 850° C., reheated to 500° C., and allowed to cool in air.	65 to 75	70 to 80	15 to 11	45 to 40	310 to 330

(*a*) Samuel Osborne and Co. (*b*) Messrs. Firth and Sons. (*c*) Messrs. Edgar Allen and Co.

TABLE LXXVI.

Effect of Chromium and Vanadium upon the Strength of Crucible Steel.

Chromium per Cent.	*Vanadium per Cent.*	*Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation in 2 Inches per Cent.*	*Reduction of Area per Cent.*
0·5	—	22·9	34·0	33	60·6
1·0	—	25·0	38·2	30	37·3
—	0·10	28·5	34·8	31	60·0
—	0·15	30·4	36·5	26	59·0
—	0·25	34·1	39·3	24	59·0
1·0	0·15	36·2	48·6	24	56·6
1·0	0·15	34·4	52·6 (*a*)	25	55·5
1·0	0·25	49·4	60·4	18·5	46·3
Ordinary carbon	crucible steel.	16·0	27·0	35	60·0
(*a*) Ordinary carbon	open hearth steel.	17·7	32·2 (*a*)	34	52·6

(*a*) Open hearth steels.

TABLE LXXVII

Properties of Vanadium Mild Steels, etc.

Material.	*Percentage Composition.*				*Elastic Limit, Tons per Square Inch.*	*Tensile Strength. Tons per Square Inch.*	*Elongation in 2 Inches per Cent.*	*Reduction of Area per Cent.*	*Impact Value.*
	Carbon.	*Manganese.*	*Chromium.*	*Vanadium*					
Mild vanadium steel ..	0·11	0·31	—	0·19	14·35	24·29	44·0	60·1	1110
Vanadium steel casting ..	0·19	0·60	—	0·076	19·80	30·93	25·5	44·9	850
Mild steel	0·18	0·40	—	—	17·62	27·80	35·0	62·6	870
Steel casting..	0·18	0·65	—	—	15·49	26·25	28·0	44·9	270
Chrome-vanadium steel casting	0·57	0·68	0·75	0·16	23·36	41·48	16·0	20·5	656
Chrome-vanadium forging..	0·26	0·50	1·00	0·16	27·65	41·48	25·0	57·3	1608
Nickel-vanadium steel (annealled)	0·24	0·72	*Nickel.* 3·40	0·15	35·38	44·51	25·0	64·0	798
Nickel-vanadium steel (oil-tempered)	0·24	0·72	3·40	0·15	58·02	60·10	18·0	64·8	626

ever, impairing its strength. The results given in Table LXXVII. show the strength properties of mild and cast vanadium-carbon steels, and also, for comparison purposes, those of mild steel, rolled, cast, and forged, and cast chrome-vanadium steel; all of these steels are in the annealed conditions. The values given in the "fatigue strength" column refer to tests made upon an alternating impact machine, being the number of alternations required to fracture the specimens; the values are therefore indicative of the relative fatigue strengths.

Nickel-Vanadium Steels.

It is possible to employ vanadium as an alternative to chromium in nickel steels, with beneficial results. The vanadium should not exceed 1·0 per cent., and should preferably be present in from 0·10 to 0·70 per cent.

The properties of these steels have been investigated by M. Leon Guiliet,* and the following are some typical results obtained by him:

TABLE LXXVIII.

PROPERTIES OF NICKEL-VANADIUM STEELS.

Material.	*Percentage Composition.*			*Elastic Limit, Tons per Sq. In.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Condition.*
	Carbon.	*Nickel.*	*Vanadium.*				
Nickel-vanadium steels.	0·20	2·0	0·7	31·25	40·62	23·5	Untempered
	0·20	2·0	1·0	40·62	53·35	22·0	,,
	0·20	12·0	0·7	76·79	89·30	6·0	—
	0·20	12·0	1·0	78·57	98·22	6·0	—
	0·20	2·0	0·7	62·98	95·01	Very small.	Tempered from 850° C., and quenched in water at 20° C.

Note.—When the low nickel content (2·0 per cent.) were heated to 850° C. and quenched in water at 20° C., the tensile strength and elastic limit were both nearly doubled in value, the elongation being greatly reduced however.

* *Engineering Magazine*, April, 1906.

Copper Steels.

Steels containing from 0·5 to 4·0 per cent. of copper somewhat resemble the nickel steels in their strength properties.*

The presence of copper refines the structure of carbon steel, and the strength increases with the copper content, and with a reduction of the carbon content (from 1·0 to about 0·2 per cent.).

When more than about 4 per cent. of copper is present the metal cannot be forged or rolled satisfactorily.

Steels containing 0·16 per cent. carbon and 4 per cent. copper are equal to nickel steels in tensile strength and ductility, and in the hardened state copper steels of this class possess a fair degree of elasticity and elongation. The electrical conductivity of these steels is better than that of nickel steels, being a maximum for steels containing 0·15 carbon and 2·0 copper, 0·35 carbon and 1·7 copper, and 0·7 to 1·0 carbon and 0·5 copper, respectively.

Annealing whilst leaving the steels with the same strength characteristics greatly reduces the differences observed in the case of untreated steels. Quenching restores the differences found in copper steels in the cast state.

Stainless Steel.

When a high percentage of chromium is present in a steel of medium or low carbon content, a high tensile steel is obtained which is almost entirely non-corrodible.

The chromium content should be between the limits 11 to 15 per cent. This "stainless" steel is an air-hardening one, although it responds to oil-hardening treatment, and it therefore requires handling with care in manufacturing articles. This steel possesses the property of being able to successfully resist the ordinary corrosive action of the weather, organic acids, sea-water, and oxidising influences.†

* An account of the experiments made upon copper steels by Pierre Breuil is given in the *Journal of the Iron and Steel Institute*, 1907.

† A polished cylinder of this steel, given to the author by Messrs. Firth and Sons, was found to retain its polish without rusting when left out in the open for several months, and after three years, or more, is still quite bright and untarnished.

Fig. 176.—Hardened Stainless Steel. Etched. × 500.

Fig. 177.—Tempered Stainless Steel. Etched. × 500.

Figs. 176 and 177 show the micro-structure of this steel in the hardened and tempered states respectively. "Stainless" steel can be obtained in tensile strengths (when heat-treated) up to

90 tons per square inch with 8 per cent. elongation and 18 per cent. reduction of area, and with a corresponding Brinell hardness of 390.

Stainless steel would therefore appear to possess excellent qualities for aeroplane work, streamlined wires, clips, fittings, petrol engine valves, seaplane fittings, cutlery, etc. Its advantage over 25 per cent. nickel steel lies in the fact of its greater strength and hardness, and better non-corrosive properties; moreover, it is more suitable for inlet and exhaust valves, as it does not stretch so much under a given stress. Stainless steel is now much used for "rustproof" cutlery, as it retains its polish when used for domestic purposes, such as when subjected to the action of the juices of fruits, vegetables, vinegar, soda-water, etc.

The following is the composition of this steel:*

Carbon	0·30 to 0·50	per cent.
Silicon	0·30 (max.)	,,
Manganese	0·20 to 0·50	,,
Sulphur	0·04 (max.)	,,
Phosphorus	0·04 ,,	,,
Chromium	11·0 to 14·0	,,

When this steel is oil-hardened at 900° C., and tempered at 600° C., it has the following mechanical properties:

Yield point	38 to 45 tons per square inch.
Tensile strength	50 to 60 ,, ,,
Elongation on 2 inches	18 per cent.
Reduction of area	45 ,,
Izod impact value	40 foot-pounds.

This steel responds well to heat treatment, and its properties may be varied over a wide range by suitably performing these operations. Table LXXIX.,† on p. 381, shows some of the results obtained by heat-treating stainless steel in the manner indicated.

* Messrs. Firth and Sons. (This steel was first discovered in the Brown-Firth Research Laboratory, Sheffield.)

† Dr. Hatfield.

Spring Steels.

There is a number of carbon and alloy steels used for springs of various kinds; these may be summarized as follows:

(*a*) High carbon steel.
(*b*) High silicon steel.
(*c*) Silico-chrome steel.
(*d*) Silico-manganese steel.
(*e*) Chrome-vanadium steel.

The best materials* for springs are those which can store up the greatest amount of work, or energy, in a given weight or volume of spring material, without permanent deformation.

Steel for springs should have as high elastic limit as possible, and a corresponding high deformation or deflection value; further, it is essential for aircraft and automobile purposes that the spring steel should be of maximum strength against fatigue effects and shocks.

Carbon Steels.

Carbon spring steels possess the advantage that they are comparatively cheap to make and easy to manipulate; moreover, they give satisfactory results for parts of minor importance.

The following is a standard specification for spring steel:

Carbon	0·90 to 1·10 per cent.
Manganese	0·25 to 0·50 ,,
Silicon	0·15 to 0·25 ,,
Sulphur	not over 0·04 ,,
Phosphorus	,, 0·04 ,,
Copper	0·03 to 0·05 ,,

The tensile strength of such steel, when heat-treated varies from 40 to 50 tons per square inch with from 16 to 20 per cent. elongation.

High Silicon Steel.

This type of steel really includes the silico-manganese steels, and may, perhaps, be grouped with them.

Silicon steel is now more or less standardized for automobile leaf springs; a typical composition is as follows:

* See pp. 14, 15, and 16.

TABLE LXXIX.

Effect of Heat Treatment upon the Properties of Stainless Steel.

(Size of material, $1\frac{1}{8}$ inch diameter by $7\frac{1}{2}$ inches long.)

Nature of Heat-Treatment.	*Yield Point, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Reduction of Area per Cent.*	*Brinell No.*	*Mean Izod Impact Foot-Pounds.*
Air-hardened at 875° C. and tempered at 500° C.	70·9	85·9	13·0	40·5	380	—
Air-hardened at 875° C. and tempered at 600° C.	44·5	53·6	21·0	59·2	241	69
Air-hardened at 875° C. and tempered at 700° C.	31·6	45·2	26·0	64·6	202	86
Air-hardened at 875° C. and tempered at 800° C.	31·6	43·3	27·0	64·7	269	33
Oil-hardened at 875° C. and tempered at 500° C.	72·6	90·5	8·0	18·2	387	—
Oil-hardened at 875° C. and tempered at 600° C.	39·4	52·0	20·0	56·9	241	72
Oil-hardened at 875° C. and tempered at 700° C.	34·8 ?	47·1	25·5	63·8	219	86
Oil-hardened at 875° C. and tempered at 800° C.	59·1	71·6	4·0	11·7	275	22
Water-hardened at 875° C. and tempered at 500° C.	70·9	90·2	12·0	34·2	387	—
Water-hardened at 875° C. and tempered at 600° C.	40·3	53·9	22·0	59·8	248	82
Water-hardened at 875° C. and tempered at 700° C.	29·5	45·8	25·8	64·7	217	86
Water-hardened at 875° C. and tempered at 800° C.	30·6 ?	48·0	18·0	59·2	196	86

Note.—Tempering in all cases was carried out for 1 hour at the temperatures stated.

Carbon	0·50 per cent.
Manganese	0·65 ,,
Silicon	1·75 ,,
Phosphorus	not over 0·04 per cent.
Sulphur	,, 0·04 ,,

This steel is widely used for large laminated or leaf springs volutes and spiral springs for locomotive automobile and aircraft work. The heat treatment of this steel requires careful attention, for different shapes and sizes of springs required different quenching media, and temperatures of hardening and tempering.

The tensile strength of the above steel in the annealed state varies from 30 to 40 tons per square inch with from 20 to 25 per cent. elongation. In the heat-treated state the tensile strength varies from 50 to 90 tons per square inch, according to the mode of heat treatment, with from 15 to 5 per cent. elongation.

The following test results refer to a special silico-manganese steel,* heat-treated according to the maker's instructions:

Elastic limit	85 to 95 tons per square inch.
Tensile strength	95 to 105 ,, ,,
Elongation on 2 inches	12 to 8 per cent.
Contraction of area	30 to 25 ,,

This steel is particularly suitable for all kinds of automobile leaf springs.

Silico-Chrome Steels.

Automobile springs are often made of a steel of medium carbon content containing about 1 per cent. of silicon and 0·7 per cent. of chromium.

The following is a typical composition:†

Carbon	0·55 to 0·60 per cent.
Silicon	0·96 to 1·15 ,,
Sulphur	0·025 to 0·04 ,,
Manganese	0·30 to 0·35 ,,
Phosphorus	0·01 to 0·02 ,,
Chromium	0·65 to 0·80 ,,

Leaf springs made in this material, properly hardened and tempered, are usually tested in compression to about one-third of the deflection necessary to flatten the top or longest leaf.

* Sir Joseph Jonas, Colver and Co., Sheffield.

† "Materials used for Motor Bus Construction," *Engineering*, January 15, 1913.

The test is repeated upon the individual leaf members, and finally upon the assembled spring, which is carefully measured before and after loading for permanent set. The spring testing machines mentioned in Chapter III. are very suitable for the above tests.

The following particulars refer to a silico-chrome spring steel known as Vicker's B.C.T. steel.* It has a lower silicon, but a higher manganese, content than the previously mentioned steel.

Chemical Composition, by Analysis:

Carbon	0·55 to 0·65 per cent.
Silicon	0·20 to 0·50 ,,
Manganese	0·50 to 0·80 ,,
Sulphur	0·04 (max.) ,,
Phosphorus	0·04 (max.) ,,
Chromium	0·45 to 0·70 ,,

This steel can be heat-treated in many ways, depending upon the purpose for which it is required; its tensile strength can be varied from 55 to 100 tons per square inch, with minimum percentage elongations of 15 and 7 per cent. respectively.

When normalized at 820° C., this steel possesses the following mechanical properties.

Yield point	(min.) 30 tons per square inch
Tensile strength	55 to 65 ,, ,, ,,
Elongation on 2 inches (× 0·564-in. diameter)	(min.) 15 per cent.
Brinell hardness number . ..	235 to 277

When oil hardened at 820° C., and tempered at from 550° C. to 600° C. the following results were obtained :

Yield point	(min.) 40 tons per square inch.
Tensile strength	60 to 70 ,, ,, ,,
Elongation on 2 inches (× 0·564-in. diameter)	(min.) 15 per cent.
Reduction of area	(min.) 40 ,,
Brinell (approximately)	255 to 341

Test results from this steel treated as *Spring Plates* not exceeding $\frac{3}{8}$ inch thick, oil-hardened at 820° C., and tempered at from 450° C. to 500° C., were as follows:

Yield point	(min.) 75 tons per square inch.
Tensile strength	90 to 100 ,, ,, ,,
Elongation on 2 inches .. .	(min.) 7 per cent.
Brinell (approximately)	418 to 477

* Manufactured by Messrs. Vickers, Ltd., Sheffield.

This steel is also very suitable for gear-wheels, special machine gun barrels, dies, and drop-stamps.

When used for gears, the gear blanks are first heat-treated so as to give the highest tensile strength compatible with sufficient ease in machining the teeth surfaces, and these, after machining, are locally hardened by a special process.*

Chrome-Vanadium Spring Steel.

This steel is widely used in automobile work, and is a serious competitor to the silico-manganese steels; it is understood to yield rather better and more uniform results after suitable heat-treatment than the latter steel.

A typical composition is as follows:

Carbon	0·50 per cent.
Manganese	0·65 ,,
Chromium	0·90 ,,
Vanadium	0·18 ,,
Sulphur	not over 0·04 per cent.
Phosphorus	,, 0·04 ,,

In the annealed state, the tensile strength is from 30 to 40 tons per square inch, with a yield ratio of from 0·75 to 0·80, and an elongation of from 15 to 20 per cent.

When correctly heat-treated, the tensile strength may be varied from 80 to 125 tons per square inch, with a corresponding elongation of from 12 to 4 per cent., respectively.

In the case of most spring steels, the heat-treatment is specified by the steel manufacturers and should be carefully followed.

Manganese Steel.

Practically all carbon and alloy steels contain small quantities of manganese, as will be seen from the chemical analyses shown in Table LXVIII.; it is advantageous and essential to retain small amounts of manganese, for it prevents the formation of iron oxide during melting, heating, and forging operations, and neutralizes the sulphur present, besides improving the strength qualities. It is usually reckoned that each 0·01

* See Chapter VIII. for particulars of Vickers' Hardening Process.

per cent. of manganese increases the tensile strength of carbon steel by from 100 to 400 pounds per square inch, depending upon whether the steel is acid or basic. When the manganese is present in quantities varying from 12 to 15 per cent., the steel is non-magnetic* and tough. If quenched from 950° C. the non-magnetic and exceedingly tough qualities are combined.

Treated in the usual manner for ordinary commercial use, by being heated to about 1000° C., and quenched in water, the material is very tough and strong, and it is practically non-magnetic. Heated at about 520° C. for 600 hours it acquires an amount of magnetism equal to about 60 per cent. of that of pure iron, and at lower temperatures it also becomes magnetic, though the change is much slower. Experiments have been tried on the destruction of the magnetic quality induced by heat treatment at 520°. The material having been heated for a certain time was quenched in water and then again heated, when it was found that a temperature of 550° or less did not diminish the magnetism, which, however, is rapidly diminished at a temperature exceeding 640°, and is almost completely destroyed by a few minutes' heating at 750°. It was anticipated that this comparatively sudden change would be accompanied by a perceptible absorption of heat, and the heating curves clearly show such an absorption, confirming the existence in the material of a change point at about 700°.

While manganese steel after ordinary cooling in air following casting or forging is comparatively brittle, hard, and non-magnetic, after water-toughening by quenching from 1000° it becomes exceedingly ductile, though remaining non-magnetic. But any treatment of the water-toughened material which has the effect of making it magnetic, even to a small extent, also renders it hard and brittle, and pieces having 1 per cent. of the magnetism of pure iron, or even less, have so far lost their toughness as to be unfit for practical use. As the magnetism increases the hardness usually increases also, but the addition to the hardness is small as compared with that

* The metallography of high manganese steel is considered in Chapter IV.

accompanying the first traces of magnetism. The change from the ductile to the brittle form is accompanied by well-marked changes in the microstructure.

As distinct from most other steels, the effect of tempering this steel is to make it progressively harder and magnetic; the original tough and non-magnetic condition, may, however, be restored by a further heating to from 900° C. to 950° C. and quenching.

The composition of a typical non-magnetic manganese steel is as follows:

Carbon	1·0 to 1·3 per cent.
Silicon	0·3 to 0·4 ,,
Manganese	12 to 15 ,,
Phosphorus	0·3 per cent.
Sulphur	0·03 ,,

The strength of sheet manganese steel of this composition is as follows:

Yield point	19·0 tons per square inch.
Tensile strength	35·0 ,, ,, ,,
Elongation	20 per cent.
Reduction of area . ..	50 ,,

Sheet manganese can be bent over double without cracking. Manganese steel cannot be machined, but may be punched or sheared; it is usual to forge this steel first, water toughen, and then to finish it by grinding processes.

Manganese steel has been used in aeroplane construction for sheet metal pressings, clips, lugs, etc., but it cannot be welded.

Manganese Steel Castings.—Castings may be made from this high manganese steel, which are sound, but brittle.

The casting may be considerably improved by heating it almost to whiteness and then quenching in water; the effect is to increase both the strength and the ductility.

The contraction of the castings is rather marked, being about $\frac{5}{8}$ inch per foot.

Samples taken from typical castings gave the following results:

Elastic limit	20 to 22 tons per square inch.
Tensile strength	38 to 42 ,, ,, ,,
Elongation on 2 inches ..	10 per cent.

Manganese steel castings are employed for the jaws of stone crushing mills, large motor sprockets and brackets.

Tungsten Steel.

When about 5 to 6 per cent. of tungsten is present in steel containing from 0·60 to 0·80 per cent. carbon, the resulting steel is particularly suitable for the permanent magnets of electrical machines, such as magnetos, measuring instruments, etc.

The following is a typical composition:

Carbon	0·6 to 0·8 per cent.
Silicon	0·30 (max.) ,,
Manganese	0·2 to 0·4 ,,
Sulphur	0·04 (max.) ,,
Phosphorus	0·04 (max.) ,,
Tungsten	5·0 to 6·0 ,,

The tensile strength properties of hardened tungsten steel are of little importance in view of its application.

The hardness value of an existing well-known tungsten steel magneto magnet* was found to be 652.

The magnetic properties of this steel are very good, for it has a high *coercive force,* and high permanence or remanent magnetism value.

The Coercive force of a suitably hardened 5 per cent. tung sten steel magnet varies from 55 to 65 C.G.S. units.

The Remanent Flux Density is about 10,000 C.G.S. units.

Tool Steels.

Tungsten also enters into the composition of modern high-speed tool steels, and the well-known mushet, or self-hardening steel is one of this class.

The following is the composition of a self-hardening or mushet tool steel:

Carbon	1·50 to 2·00 per cent.
Tungsten	4·0 to 6·0 ,,
Chromium	0·25 to 0·30 ,,
Manganese	0·30 to 0·50 ,,
Sulphur	0·02 to 0·04 ,,
Phosphorus	0·02 to 0·04 ,,

* Dr. Hatfield.

This steel when heated to redness and allowed to cool has a glass-hardness; it can only be worked in the red-hot stage. It may, however, be ground when cold.

In the case of some high-speed steels, such as the one given below, an air-blast, oil or water medium, is often employed to obtain increased hardness, for cutting purposes. Molybdenum, chromium, and vanadium often enter into the composition of high-speed steels. The following is the composition of a modern high-speed steel:

Carbon	0·60 to 0·80 per cent.
Tungsten	8·0 to 16·0 ,,
Chromium	3·0 to 5·0 ,,
Manganese	0·15 to 0·25 ,,
Silicon	0·05 to 0·25 ,,
Sulphur	0·01 to 0·03 ,,
Phosphorus	0·01 to 0·03 ,,

It will be noticed that the carbon content is lower than in the case of mushet steel, but that the tungsten and chromium contents are much higher.

The effect of adding small quantities of vanadium (from 0·10 to 0·30 per cent.) to high-speed steel, containing high tungsten and chromium contents is to raise the critical point so that the tool can withstand a higher temperature without losing its hardness, that is to say, it can work at a higher cutting speed.

Vanadium high-speed steel is harder and more durable than ordinary high-speed and tool steels.

Cobaltchrom Steel.*

This is an air-hardening high-speed steel, which does not, however, contain any tungsten in its composition. It is suitable for milling cutters, twist drills, reamers, taps, lathe, and other machine tools, and it is claimed that it gives at least the same endurance as in the case of tungsten steel, together with a better finish.

It is supplied in bars of all commercial sections, and in sheets from $\frac{1}{32}$ inch in thickness, upwards.

Cobaltchrom steel is recommended for petrol engine valves,

* Messrs. Darwin and Miller, Sheffield.

high endurance drawing and blanking dies, shear blades, press tools, and hack-saw blades.

This steel is usually air-hardened from 1000° C., but before drawing the tool or part from the muffle furnace the temperature is allowed to fall slightly, after which the tool or part is allowed to cool in still air until it becomes "black-red," when it is quenched in whale oil. For extreme hardness it is quenched out in tepid water. For shock tools and similar objects, air cooling from 1000° C. down to the ordinary temperature of the air, without quenching, is recommended.

Ball-Bearing Steels.

In the past, a number of different steels have been employed for ball and roller bearings, including case-hardening carbon and alloy steels, carbon and alloy steels.

The steels chiefly used at the present time are chromium and chrome-tungsten steels.

The following analyses refer to the two best steels obtained —results of a large number of tests* upon ball-bearings made from over four hundred different steels:

	A.	B.
Carbon	1·12 per cent.	0·95 per cent.
Silicon	0·015 ,,	0·014 ,,
Phosphorus	0·017 ,,	0·018 ,,
Manganese	0·19 ,,	0·025 ,,
Sulphur	0·019 ,,	0·019 ,,
Chromium . .	0·25 ,,	1·25 ,,
Tungsten	—	0·25 ,,

The best ball-bearings are only made from alloy steels such as the above, the material, after heat treatment being extremely hard, tough, and of fine texture.

Ball-bearings for light loads and inexpensive parts are often made of a case-hardening carbon or nickel-steel of good quality; where carbon steel is employed it should be of the purest grade—such as that made from electrolytic or Swedish iron.

The data given in Table LXXXIII. refers to the crushing strength of tool steel balls.

* *Machinery.*

TABLE LXXX.

COMPOSITIONS OF AUTOMOBILE AND AIRCRAFT STEELS (ACTUAL ANALYSES).

Material and Part.	Composition per Cent.									
	Carbon Combined.	*Carbon Graphitic.*	*Silicon.*	*Manganese.*	*Sulphur.*	*Phosphorus.*	*Nickel.*	*Chromium.*	*Vanadium.*	*Tungsten.*
C.H. mild steel (gudgeon pin)	0·12	—	0·18	0·50	0·04	0·03	—	—	—	—
Front axle, steel drop forgings, etc.	0·28 to 0·33	—	0·05 to 0·10	0·50 to 0·64	0·03 to 0·04	trace to 0·04	—	—	—	—
3 per cent. nickel steel crank-shaft	0·38 to 0·45	—	0·15 to 0·175	0·60 to 0·75	0·03 to 0·04	trace to 0·04	3·00 to 3·30	—	—	—
Chrome - vanadium steel crank-shaft	0·40 to 0·425	—	0·12 to 0·18	0·50 to 0·65	0·02 to 0·04	0·02 to 0·04	—	1·30 to 1·50	0·15 to 0·19	—
Chrome - vanadium steel eccentric shafts	0·38 to 0·43	—	0·17 to 0·22	0·50 to 0·75	0·02 to 0·045	0·02 to 0·03	—	1·20 to 1·50	0·175 to 0·25	—
Nickel-chrome steel for eccentric shafts	0·30 to 0·35	—	0·14 to 0·17	0·60 to 0·70	0·02 to 0·03	trace to 0·03	3·40 to 3·60	0·75 to 0·80	—	—
Air-hardening nickel-chrome steel for differential shafts	0·28	—	0·224	0·428	0·01	0·013	1·436	4·55	—	—
3 per cent. nickel steel for swivel forks and steering levers (stampings)	0·30 to 0·35	—	0·15 to 0·175	0·60 to 0·75	0·03 to 0·04	trace to 0·025	3·00 to 3·30	—	—	—
Case-hardened Swedish charcoal steel for chain gear-wheels	0·09 to 0·14	—	trace to 0·03	0·02 to 0·30	0·015 to 0·020	trace only	—	—	—	—
Steel castings	0·20 to 0·24	—	0·18 to 0·22	0·60 to 0·70	0·015 to 0·020	0·024 to 0·040	—	—	—	—

TABLE LXXXI.

MECHANICAL TEST RESULTS FOR AUTOMOBILE STEELS, ETC.

(For materials given in Table LXXXI.)

Material and Part.	*Yield Point.*	*Tensile Strength.*	*Elongation per Cent. on 2 Inches.*	*Reduction of Area.*	*Izod Impact Test.*	*Brinell Hardness.*
C.H. mild steel gudgeon pin untreated	14	27	35	60	—	—
Front axle steel drop forgings*	28 to 32†	40 to 46	25 to 20	65 to 60	70 to 60	—
3 per cent. nickel crank-shaft steel*	37 to 42†	55 to 60	18 to 16	55 to 45	—	—
Chrome-vanadium crank-shaft steel	37 to 42†	50 to 55	18 to 17	55 to 45	—	—
Chrome-vanadium steel for eccentric shafts* ..	39 to 44†	55 to 60	21 to 18	60 to 45	—	—
Nickel-chrome steel for eccentric shafts*	38 to 45†	53 to 58	20 to 17	55 to 45	—	—
Air-hardening nickel-chrome steel for differential shafts (hardened)*	102†	108	12 to 15	30 to 35	—	—
Ditto. Untreated, or soft	45 to 48†	57 to 60	26 to 23	68 to 63	—	—
3 per cent. nickel for swivel forks and steering arms, etc.*	33 to 38†	45 to 50	22 to 20	60 to 55	—	240 to 250
Steel castings (Daimler)	20·5†	30	22 to 25	35 to 40	—	—
Charcoal steel case-hardened gear wheels* ..	15 to 18†	21 to 25	30 to 25	70 to 60	—	—
Spring steel (silico-manganese) for automobile leaf springs‡	85 to 95†	95 to 105	12 to 8	30 to 25	—	—
Nickel-chrome gear steel (air-hardening)‡.. ..	90 to 100†	105 to 115	15 to 10	35 to 25	15 to 10	447
Ditto. Hardened in oil‡	95 to 100†	110 to 120	12 to 8	30 to 20	12 to 8	495 to 512
Medium carbon steel, for crank shafts, front-axles, aero-engine cylinders (untreated)‡	24†	42	25	40	—	187
Ditto. Heat-treated	30	45	25	50	—	202

* In heat-treated condition. † Elastic limit. ‡ Jonas Colver and Co., Ltd.

TABLE LXXXII.

FERROUS MATERIALS USED IN AEROPLANE ENGINES.

Name of Part.	Composition per Cent.									
	Carbon Combined.	*Carbon Graphitic.*	*Silicon.*	*Manganese.*	*Sulphur.*	*Phosphorus.*	*Nickel.*	*Chromium.*	*Vanadium.*	*Tungsten.*
Cast iron cylinder head ..	0·91	2·57	1·60	0·70	0·131	0·34	—	—	—	—
Cast iron piston	0·83	2·42	1·29	0·83	0·111	0·30	—	—	—	—
Cast iron gudgeon pin floating bush	0·65	2·39	1·43	0·76	0·146	0·47	—	—	—	—
Steel cylinder barrel	0·49	—	0·33	1·01	0·028	0·054	—	—	—	—
Steel cylinder water jacket ..	0·25	—	0·27	0·63	0·032	0·037	—	—	—	—
C.H. steel gudgeon pin.. ..	0·28	—	0·23	0·48	0·028	0·022	—	—	—	—
Nickel-chrome connecting rod ..	0·15	—	0·33	0·31	0·027	0·010	1·42	0·49	—	—
Nickel-chrome connecting rod ..	0·13	—	0·19	0·52	0·033	0·014	2·83	0·29	—	—
Nickel-chrome crank-shaft* ..	0·31	—	0·31	0·63	0·030	0·015	4·01	0·83	—	—
Nickel-chrome crank-shaft† ..	0·41	—	0·29	0·64	0·052	0·042	2·36	0·86	—	—
Nickel-chrome cam-shaft ..	0·40	—	0·25	0·23	0·022	0·040	3·46	0·68	—	—
Nickel-chrome gear-wheel ..	0·30	—	0·27	0·74	0·025	0·030	4·17	1·39	—	—
Nickel-chrome inlet valve ..	0·53	—	0·30	0·48	0·032	0·044	4·01	0·51	—	—
Chromium inlet valve	1·82	—	0·52	0·10	0·048	0·010	—	10·47	—	—
Nickel-chrome exhaust valve ..	0·10	—	0·20	0·26	0·019	0·023	3·62	1·16	—	—
Chromium exhaust valve ..	1·75	—	0·58	1·10	0·048	0·013	—	10·85	—	—
Steel valve springs	0·52	—	0·07	0·59	0·060	0·031	—	—	—	—

* Mechanical test results for specimens from this crank-shaft yield point, 59 to 63; tensile strength, 63 to 67 tons per square inch; elongation on 4 inches, 7·2 to 15·1 per cent.; reduction of area, 5·5; Izod impact test, 12 to 17 foot-pounds, except transversely to web, when it was 5·5 foot-pounds.

† The mechanical tests upon specimens from this crank-shaft gave a yield point of 55·7, and tensile strength of 62·0 tons per square inch, with 13·5 per cent. elongation on 2 inches and 23·5 reduction in area.

TABLE LXXXIII.

CRUSHING STRENGTH OF TOOL STEEL BALLS.

Size, Inches.	*Crushing Load, Pounds.*	*Size, Inches.*	*Crushing Load, Pounds.*	*Size, Inches.*	*Crushing Load, Pounds.*
$\frac{1}{16}$	390	$\frac{1}{4}$	6215	$\frac{5}{8}$	39,000
$\frac{3}{32}$	875	$\frac{5}{16}$	9940	$\frac{3}{4}$	56,250
$\frac{7}{64}$	1562	$\frac{3}{8}$	14,000	$\frac{7}{8}$	76,000
$\frac{1}{8}$	2450	$\frac{7}{16}$	19,000	1	100,000
$\frac{3}{16}$	3496	$\frac{1}{2}$	25,000	$1\frac{1}{2}$	225,000
$\frac{7}{32}$	4780	$\frac{9}{16}$	31,500	2	400,000

[*Machinery.*]

Note.—Alloy steel balls are from 20 to 30 per cent. stronger than tool steel balls.

Automobile Materials (Ferrous).

Table LXXX. gives some actual examples of the composition of ferrous materials employed in automobile work, the corresponding mechanical test results being given in Table LXXXI.

Typical Examples of Aircraft Materials (Ferrous).

Aeroplane Engines.—The chemical analyses and mechanical test results on p. 392 refer to modern aeroplane engines, in which the property of maximum strength for weight, in the materials employed, is of the utmost importance.

TABLE LXXXIV.

FERROUS MATERIALS EMPLOYED FOR AUTOMOBILE MEMBERS AND AERO-ENGINES.

Name of Part.	*Materials Employed.*
ENGINES.	
Cylinders	Cast iron (fine grained white, low carbon content), 40 ton steel for aero-cylinders, aluminium alloy with steel or iron liners.
Pistons	Cast iron (fine grained), medium carbon steel or aluminium alloy.
Piston rings	Chilled cast iron (mottled).
Crank-shaft	40 ton steel, 3 per cent. nickel steel, chrome-vanadium, nickel-chrome (oil-hardened).

FERROUS MATERIALS—*continued.*

Name of Part.	*Materials Employed.*
ENGINES—*continued*	
Camshaft	Case-hardening nickel steel, C.-H. carbon steel, C.-H. nickel-chrome steel.
Connecting rod ..	Nickel-chrome steel, chrome-vanadium steel, 40 ton steel, air-hardening nickel-chrome steel (100 tons).
Connecting rod bolts ..	3 per cent. nickel steel or nickel-chrome steel.
Gudgeon pins	Case-hardening nickel-steel or C.-H. mild steel, C.-H. nickel-chrome steel.
Starting dogs	Case-hardening nickel steel or C.-H. mild steel, C.-H. nickel-chrome steel.
Inlet valves	Tungsten steel, chrome valve steel, nickel-chrome steel.
Exhaust valves ..	Tungsten steel, chrome valve steel, 25 per cent. nickel steel.
Gears, high duty ..	(A) Air or oil hardening nickel-chrome steel.
Gears, normal	(B) Case-hardening, carbon, nickel or nickel-chrome steels.
Valve springs	Silicon-manganese steel, nickel-chrome steel, carbon spring steel.
Ball bearings ..	Nickel-chrome steel (oil-hardened). Good carbon steel (case-hardened).
TRANSMISSION.	
Clutch coupling ..	Nickel-chrome steel, 3 per cent. nickel steel.
Coupling pins	Case-hardening nickel or mild steel.
Spiders	Nickel-chrome steel, chrome-vanadium steel, or 40 ton steel.
Gear shafts	Nickel-chrome steel, chrome-vanadium steel, or 40 ton steel.
Constant mesh pinions	Case-hardening nickel steel, or mild steel.
Striking lever shafts ..	Case-hardening nickel steel, or chrome-vanadium steel.
Sliding pinions.. ..	Case-hardening nickel steel, or mild steel.
Universal joint blocks..	Case-hardening nickel steel, or mild steel.
Universal joint boss ..	Nickel-chrome steel.
Foot brake drum ..	Mild steel.
Foot brake shoes ..	Cast iron (medium).
Worm and worm shaft	Case-hardening mild steel.
Brake and operating rods	Bright drawn mild steel.
AXLES.	
Tubes	40 ton steel, nickel-chrome steel.
Shafts	Nickel-chrome steel, 3 per cent. nickel steel.
Bevel pinions	Case-hardening mild steel, nickel-chrome steel (case-hardening).
Crown wheel	Case-hardening mild steel, nickel-chrome steel (case-hardening). (Also 100 ton air-hardening nickel-chrome steels.)
Spider	Nickel-chrome steel, chrome-vanadium, medium carbon steel.
Cams (brake)	Case-hardening nickel steel, C.-H. mild steel.
Propeller shaft.. ..	Nickel-chrome steel, chrome-vanadium steel.

FERROUS MATERIALS—*continued.*

Name of Part	*Materials Employed.*
AXLES—*continued*	
Torque tube	40 ton steel, nickel-chrome steel.
Radius rod	Bright drawn mild steel, or chrome-vanadium steel.
Tie rods	Bright drawn mild steel, or chrome-vanadium steel.
Leaf springs	Chrome-vanadium steel, silico-manganese steel, high silicon steel, chrome-silicon steel.
CHASSIS AND STEERING.	
Chassis, frame	Nickel steel, mild steel, nickel-chrome steel.
Shackles	Nickel-chrome steel, chrome-vanadium steel, medium carbon steel.
Front axle	Nickel-chrome steel, chrome-vanadium steel, good carbon steel.
Cross members.. ..	Nickel steel, mild steel.
Steering swivel ..	Nickel-chrome steel, chrome-vanadium steel, good carbon steel.
Swivel pins	Nickel-chrome steel, chrome-vanadium steel, good carbon steel.
Steering arms	Nickel-chrome steel, chrome-vanadium steel, good carbon steel.
Steering links	Nickel-chrome steel, chrome-vanadium steel, good carbon steel.
Worm	Case-hardening mild steel.
Sector	Case-hardening mild steel.
Worm shaft	Good mild steel, nickel steel.
Sector shaft	Good mild steel, nickel steel.
Steering pin joints ..	Case-hardening nickel steel.
Ball joints . ..	Case-hardening nickel steel.
Spring clips	Good mild steel.

CHAPTER VII

COMMERCIAL FORMS OF FERROUS MATERIALS

Sheet Steels.

MOST of the steels hitherto considered can be produced in the form of sheets by successive rolling processes, during which the material becomes hardened, unless frequently annealed.

The steels employed for sheets may be broadly divided into two classes—namely, (*a*) Weldable Steels and (*b*) Unweldable Steels.

Class (*a*) includes the low and medium carbon steels and also low nickel steels.

Class (*b*) includes high carbon and alloy steels such as nickel-chrome, chrome-vanadium, manganese, etc.

The weldable steels can be hammered and bent cold to fairly sharp angles without cracking.

The high tensile steels can generally be bent cold in the annealed state, but require subsequent heat treatment in order to develop their full mechanical strength properties.

Table LXXXV. gives the mechanical properties of the principal steels used in the sheet form.

Mild and Low Carbon Sheet Steels.

These steel sheets are more widely employed in automobile work than any other, for pressed parts such as bonnets, mudguards, wings, body work, and sheet metal fittings. Mild steel sheets are also employed in aircraft work for fittings requiring welding, for bent-metal parts, and for clips and fittings which are not heavily stressed.

This steel can be easily punched, drilled, sheared, and bent to sharp angles without cracking, and is particularly suited to hand sheet metal work.

TABLE LXXXV.

PROPERTIES OF SHEET STEELS.

Material.	*Condition.*	*Yield Point. Tons per Square Inch.*	*Tensile Strength. Tons per Square Inch.*	*Elongation on 2 Inches per Cent.*	*Elongation on 2 Inches per Cent.*
Mild steel sheet.	As rolled.	18	26	30	40
I.A.S.B. extra soft carbon steel sheet.	Annealed (specimens cut in any direction).	13·4*	22·3*	25* (on 4 inches)	—
I. A. S. B. soft carbon steel sheet.	Annealed (specimens cut in any direction).	16·0*	26·8*	22* (on 4 inches)	—
I.A.S.B. one-half hard carbon steel sheet.	Annealed (specimens cut in any direction).	20·5*	33·5*	18* (on 4 inches)	—
"Best quality" aeroplane steel sheets R.A.F.	As taken from sheet.	25*	50*	10* (on 4 inches)	20*
I.A.S.B. standard alloy steel sheets.†	Heat-treated according to manufacturer's instructions.	33·5*	44·5*	15 (on 4 inches)	—
Firth's CN/1 crucible 5 per cent. nickel steel sheet.	As rolled. Annealed. Heat-treated.	26 29 30	34·5 35 40	19·5 24 26	33 35 40
Firth's 25 per cent. nickel steel sheets.	As rolled. Heat-treated.	36·6 28	52·6 42·9	20 34·5	23·3 37·9
Firth's non-corrodible high tensile steel sheets.	Annealed. Heat-treated.	35 55	50·4 61	18 11·5	31·9 24·9
Bullet - proof nickel - chrome steel plate.†	Heat-treated.	60 to 80	80 to 120	10 to 4	—
Manganese steel plate.	Toughened by quenching.	20	35	10 to 15	—

* Minimum values.　　† See p. 404 for fuller particulars.

Chemical Properties.—The carbon content of this class of steel varies from 0·05 to 0·60 per cent., according to its application.

Mechanical Properties.—Specifications for sheet steels of this class require that test strips,* cut in any direction from the sheet, shall conform with certain minimum conditions of yield stress, tensile strength, elongation, and reduction of area, similar to the given in Table LXXXV. and in the specifications given upon p. 400.

It is now general to stipulate a bend test† for strips cut in any direction; the strips should be capable of being hammered over, or otherwise bent, cold, through an angle of 180°, that is to say, parallel to the original direction, to a radius equal to the thickness of the plate, without cracking on the outer surface of the bend.

A further test, often specified, is that strips, $1\frac{1}{4}$ inches wide, cut from the sheets, and with the edges rounded, shall stand reverse bending cold, through an angle of 90°, for not less than three complete reversals without fracture.

Weld Test.—It is sometimes desirable to specify that a welded joint of the sheet material shall be tested in tension, and that the efficiency of the weld shall be not less than from 80 to 85 per cent. of that of the unwelded metal.

International Aircraft Standard Sheet Steels.

Three mild steels for sheets are specified for aircraft work—namely, (*a*) Extra Soft Carbon Steel, (*b*) Soft Carbon Steel, and (*c*) Half Hard Carbon Steel.

The steels should be manufactured, or at least finished by the open-hearth, electric-furnace, or crucible process.

A sufficient discard should be made from each ingot to secure freedom from piping and undue segregation.

Sheets, unless ordered cold-rolled, shall be full pickled.

Chemical Composition.

The following are the specified percentage compositions

---

* The standard test piece for aircraft work measures 4 inches (gauge length) by $1\frac{1}{4}$ inches wide, by gauge thickness.

† For particulars of methods of testing sheet-metal, see p. 74 *et seq.*

TABLE LXXXVI.

MATERIAL SPECIFICATIONS OF CARBON SHEET STEELS.

No.	*Material.*	*Carbon.*	*Manganese.*	*Phosphorus (max.).*	*Sulphur (max.).*
1010	Extra soft carbon	0·05 to 0·15	0·30 to 0·60	0·045	0·050
1020	Soft carbon ..	0·15 to 0·25	0·30 to 0·60	0·045	0·050
1025	Soft carbon ..	0·20 to 0·30	0·50 to 0·80	0·045	0·050
1030	Half hard carbon ..	0·25 to 0·35	0·50 to 0·80	0·045	0·050
1035	Half hard carbon ..	0·30 to 0·40	0·50 to 0·80	0·045	0·050

Note.—When electric or crucible furnace steel is specified in the order the maximum allowable percentages of phosphorus and sulphur may be limited to 0·03 per cent.

Heat Treatment.

Sheets are to be well and uniformly annealed, in accordance with good commercial practice. For sheets lighter than 0·065 inch (1·65 mm.) box annealing is preferred. For sheets 0·065 inch and thicker, open annealing is preferred.

Workmanship and Finish.

It is stipulated that the sheets must be commercially flat, clean, smooth, free from seams, laminations, blisters, and other surface defects. They must be uniform in quality, and within the following margins of manufacture.

TABLE LXXXVII.

TOLERANCES FOR STANDARD STEEL SHEETS.

Thickness.		*Tolerance for 14-inch (35·6 cms.) Wide Sheets, and Under.*		*Tolerance for Sheets over 14 Inches (35·6 cms.) Wide.*	
Inches.	*Millimetres.*	*Inches.*	*Millimetres.*	*Inches.*	*Mm.*
0 to 0·020	0·51	+ 0·011 to − 0·002	+ 0·03 to − 0·05	±0·002	±0·05
0·021 to 0·030	0·54 to 0·76	+ 0·002 to − 0·003	+ 0·05 to − 0·08	±0·003	±0·08
0·031 to 0·040	0·79 to 1·02	±0·003	±0·08	±0·003	±0·08
0·041 to 0·050	1·05 to 1·27	±0·003	±0·08	±0·004	±0·10
0·051 to 0·065	1·30 to 1·65	±0·004	±0·10	±0·004	±0·10
0·066 to 0·080	1·68 to 2·03	±0·004	±0·10	±0·005	±0·13
0·081 to 0·100	2·06 to 2·54	±0·006	±0·15	±0·006	±0·15
0·101 to 0·120	2·57 to 3·05	±0·006	±0·15	±0·007	±0·18
0·121 to 0·250	3·08 to 6·35	±0·006	±0·15	±0·008	±0·20

Physical Properties and Tests.

(*a*) Specimens cut in any direction from the sheets shall have the following properties

TABLE LXXXVIII.

TENSILE TEST (*b*) MINIMUM VALUES. I.A.S.B.

No.	Material.	*Minimum Yield Point.*		*Minimum Tensile Strength.*		*Minimum Elongation per Cent.*
		Lbs. sq. in.	Kg. sq. mm.	Lbs. sq. in	Kg. sq. mm.	On 4 ins. (101·6 mm.)
1010	Extra soft carbon steel	30,000	21·09	50,000	35·2	25·0
1020, 1025	Soft carbon steel	36,000	25·31	60,000	42·18	22·0
1030, 1035	Half hard carbon steel	45,000	31·64	75,000	52·73	18·0

Bend Test.—(*c*) Strips cut from sheets shall stand being bent cold through an angle of 180° in any direction, to a radius equal to the thickness of the sheet without fracture.

(*d*) Strips 1¼ inch (31·75 mm.) wide, cut from sheets and with edges rounded, shall stand reverse bending, cold, through an angle of 90°, for not less than three complete reversals without fracture. The test is to be made in a square-nose vice, the edges over which the specimen is bent being rounded to a radius equal to three times the thickness of the sheet.

Selection of Test Specimens.

Three sheets shall be taken from each annealing box to represent the top, middle, and bottom of the stock, or one sheet from each 25, when sheets are open-annealed. One tensile, one bend, and one reverse bending test shall be made from each sheet selected.

Delivery.—It is specified that all sheets should be oiled for protection against corrosion. Sheets thinner than 0·065 inch shall be boxed, the weight of each box with contents not exceeding 220 pounds.

Sheets thicker than 0·065 inch up to 0·125 inch should be crated, the weight of the loaded crate not exceeding 220 pounds.

Sheets thicker than 0·125 inch may be bundled, the weight of such bundle not exceeding 220 pounds.

High Tensile Sheet Steels.

It is now possible to obtain in the sheet form steels, such as low and high nickel, nickel-chrome, chrome-vanadium, manganese, and similar steels, possessing almost identical properties* to those discussed in the previous chapter. In general, these sheet steels are not recommended for hand bent sheet metal

* In general, for the same chemical compositions these steels are harder, due to the rolling operations.

work, in view of the possibility of over-bending in the cold, and of the smaller elongation.

Sheet metal parts for aircraft fittings should preferably be pressed or stamped, and suitably heat-treated afterwards, in order to develop their full mechanical properties.

For aircraft work, where lightness is essential, it is possible to obtain from the manufacturers sheet steels which, when properly heat-treated, will give tensile strengths varying from 50 to 100 tons per square inch.

Low Nickel Sheet Steel.

Steel containing about 5 per cent. of nickel* and medium carbon content, closely resembling the low nickel steels mentioned in the previous chapter, is employed to a considerable extent in connexion with aircraft work.

This sheet steel may be punched, sheared, drilled, and bent cold to sharp angles without cracking, but requires a greater bending effort than in the case of low carbon steels. It is used for aircraft lugs, wiring plates, socket-clips, brackets, clips, engine plates, etc.

This steel can, with special care, be welded by the acetylene process. Annealing the rolled sheet improves its ductility without impairing the strength, and this process should be applied to all sheet metal parts after their manufacture, in order to relieve them from bending and hammering internal strains, etc.

In Table LXXXIX. the typical test results given refer to the properties of the 5 per cent. nickel steel, mentioned in the footnote, the tests being made upon 14 S.W.G. (0·080 inch) sheets.

High Nickel Sheet Steel.

Steel containing 25 per cent. nickel is frequently employed in the sheet form for aircraft fittings; this steel, which is identical with that mentioned in the previous chapter, is non-magnetic and practically non-corrodible when suitably heat-treated.

* A typical steel of this class is Firth's CN/1 crucible 5 per cent. nickel sheet steel.

TABLE LXXXIX.

PROPERTIES OF 5 PER CENT. NICKEL SHEET STEEL.

Condition.	*Yield Point. Tons per Square Inch.*	*Strength. Tons per Square Inch.*	*Elongation per Cent. in 2 Inches.*	*Reduction of Area per Cent.*
As rolled ..	26	35·4	19·5	33
Annealed ..	29	35·0	24·0	35
Heat-treated ..	30	40·0	26·0	40

Sheets made of this steel may be cold bent and machined without difficulty, in the rolled or annealed state; they can be welded, if suitable precautions are taken, and also brazed.

This material is used for aircraft clips, lugs, brackets, engine-plates, parts situated near compasses, etc.

The following are the results of tests* made upon 14 S.W.G. (=0·080 inch) sheets.

TABLE XC.

PROPERTIES OF 25 PER CENT. NICKEL SHEET STEEL.

Condition.	*Yield Point. Tons per Square Inch.*	*Tensile Strength. Tons per Square Inch.*	*Elongation per Cent. in 2 Inches.*	*Reduction of Area per Cent.*
As rolled ..	36·6	52·6	20	23·3
Heat-treated ..	28	42·9	34·5	37·9

It will be observed that the ductility is greatly increased, and the tensile and yield strengths lowered by heat treatment; the steel is, however, practically non-magnetic in this state. In order to preserve the non-magnetic property, after welding, or heating the finished parts, or material for any purpose, it is necessary to reheat them.

* Firth's NS/25 crucible 25 per cent. nickel steel sheets.

Non-Corrodible High Tensile Sheet Steels.

"Stainless," or high chromium steels* are now employed for aircraft sheet metal parts which are exposed to oxidizing atmospheric or sea-water influences. These steels successfully resist the above corrosive actions, and may be employed for all exposed fittings of aeroplanes, airships, seaplanes, etc.

By suitable heat treatments,† tensile strengths varying from 40 tons per square inch with 28 per cent. elongation, up to 90 tons per square inch with from 8 to 12 per cent. elongation, can be obtained.

It is possible to braze this material, but it is not satisfactorily to weld it, as the welded joint is liable to corrode quickly, owing to the effect of the welding heat, in altering the structure and composition of the material. After brazing or any heating operation, it is necessary to reheat this steel.

Sheets of this material may be bent cold, in the annealed state, without cracking.

The following results‡ were obtained from tests upon 14 S.W.G. (0·080 inch) sheets:

TABLE XCI.

PROPERTIES OF NON-CORRODIBLE SHEET STEELS.

Condition.	*Yield Point. Tons per Square Inch.*	*Tensile Strength. Tons per Square Inch.*	*Elongation per Cent. in 2 Inches.*	*Reduction of Area per Cent.*
Annealed ..	35	50·4	18	31·9
Heat-treated ..	55	61	11·5	24·9

High Tensile Sheet Steels.

Nickel-chrome, chrome-vanadium, and similar steels are supplied in the sheet form for high tensile fittings for automobile and aircraft work.

* See p. 377.

† Particulars of heat treatments and corresponding strengths are given on p. 381.

‡ Messrs. Firth's F.A.S. (non-corrodible) high tensile steel sheets.

In general these steels are not weldable, but can be hard or soft soldered.

Parts made from these sheets should be stamped or pressed from annealed sheets, and afterwards heat-treated. These steels are employed for parts where maximum strength and fatigue resistance combined with minimum weight are essential.

It is usual to specify, what is known as "High Tensile" sheet steel, to possess the following properties:

	Minimum Values.
Yield point	25 tons per square inch.
Tensile strength	50 " "
Elongation in 4 inches ..	10 per cent.
Reduction of area	20 "

This material should be capable of being bent over double in any direction, to a radius equal to one-half of the sheet-thickness, without cracking.

The following are the permissible limits of variation for the sheet thicknesses:

TABLE XCII.

TOLERANCES FOR SHEET STEELS.

Thickness of Sheet.		*Maximum Permissible Variation.*
Inches.	*S.W.G.*	*Inches.*
0·19 to 0·10	6 to 12	+0·006 to −0·006
0·10 to 0·048	13 to 18	+0·004 to −0·004
0·048 to 0·028	19 to 22	+0·002 to −0·002
0·028 and above.	23 and above.	+0·001 to −0·001

International Aircraft Standard Specification for Alloy Steel Sheet.

3S28—*Specifications for Alloy Steel Sheet.*

GENERAL.—1. The general specifications, 1G1, shall form according to their applicability, a part of these specifications.

MATERIAL.—2. The material for these sheets shall be chosen from the I.A.S.B. standard alloy steels listed below:

TABLE XCIII.

Chemical Composition of Standard Alloy Steels.

Nickel Steels.

No.	*Carbon.*	*Manganese.*	*Phosphorus (max.).*	*Sulphur (max.).*	*Nickel.*	*Chromium.*
2315	0·10 to 0·20	0·30 to 0·60	0·040	0·045	3·25 to 3·75	—
2320	0·15 to 0·25	0·30 to 0·60	0·040	0·045	3·23 to 3·73	—
2325	0·20 to 0·30	0·50 to 0·80	0·040	0·045	3·25 to 3·75	—

Nickel-Chromium Steels.

No.	*Carbon.*	*Manganese.*	*Phosphorus (max.).*	*Sulphur (max.).*	*Nickel.*	*Chromium.*
3120	0·15 to 0·25	0·30 to 0·60	0·040	0·045	1·00 to 1·50	0·45 to 0·75
3215	0·10 to 0·20	0·30 to 0·50	0·040	0·045	1·50 to 2·00	0·90 to 1·25
3315	0·10 to 0·20	0·30 to 0·60	0·040	0·045	2·75 to 3·25	0·70 to 1·95
3315	0·10 to 0·20	0·30 to 0·60	0·040	0·045	3·25 to 3·75	1·25 to 1·75

Chromium-Vanadium Steels.

No.	*Carbon.*	*Manganese.*	*Phosphorus (max.).*	*Sulphur (max.).*	*Chromium.*	*Vanadium (min.).*
6120	0·15 to 0·25	0·30 to 0·60	0·040	0·045	0·60 to 0·90	0·15

The composition shall be stated by the manufacturer or contractor and is further limited as follows Carbon, not over 0·25 per cent.

Manufacture.—3. (*a*) The steel shall be manufactured, or at least finished, by the open-hearth, electric-furnace, or crucible process.

(*b*) A sufficient discard shall be made from each ingot to secure freedom from piping and undue segregation.

(*c*) Sheets, unless ordered cold-rolled, shall be full pickled.

(*d*) Sheets are to be well and uniformly annealed in accordance with good commercial practice. For sheets lighter than 0·065 inch (1·65 mm.), box annealing is preferred. For sheets 0·065 inch (1·65 mm.) and thicker, open annealing is preferred.

Heat Treatment.—(*e*) The manufacturer shall state the heat treatment recommended to give the physical properties specified.

Workmanship and Finish.—4. (*a*) The sheets must be commercially flat, clean, smooth, free from seams, laminations, blisters, and other surface

defects. They must be uniform in quality, and within the stipulated margins of manufacture.

(*b*) Any sheet may be rejected because of injurious defects or faults in manufacture at any time, notwithstanding that it has previously been accepted by the inspector; it shall be returned to the manufacturer at the latter's expense. This clause shall not be taken to apply to materials fabricated after export.

PHYSICAL PROPERTIES AND TESTS.—5. (*a*) Specimens cut in any direction from the heat-treated sheets shall have the following properties:

Tensile Test.—(*b*) Minimum tensile strength, 100,000 pounds per square inch (70·30 kg. per mm.); minimum yield point, 75,000 pounds per square inch (52·73 kg. per mm.); minimum elongation, 15 per cent. in 4 inches (101·6 mm.).

Bend Test.—(*c*) Strips cut from annealed sheets shall stand being bent cold through an angle of 180 degrees, in any direction, to a radius equal to the thickness of the sheet without fracture.

(*d*) Strips 1¼ inches (31·75 mm.) wide cut from annealed sheets and with edges rounded, shall stand reversed bending, cold, through an angle of 90 degrees for not less than three complete reversals, without fracture. The test is to be made in a square-nose vice, the edges over which the specimen is bent being rounded to a radius equal to three times the thickness of the sheet.

SELECTION OF TEST SPECIMENS.—6. Three sheets shall be taken from each annealing box to represent the top, middle, and bottom of the stack, or one sheet from each twenty-five when sheets are open annealed. One tensile, one bending, and one reverse bending test, shall be made from each sheet selected.

DIMENSIONS AND TOLERANCES.—7. The dimensions and tolerances shall be those given in the table below and in the specifications 3S11. The thickness will be specified in decimals of an inch or millimetres

TABLE XCIV.

TABLE OF TOLERANCES FOR STANDARD STEEL SHEETS.

Thickness.		*Tolerance for Sheets 14 Inches (33·6 cm.) Wide and Under.*		*Tolerance for Sheets over 14 Inches (35·6 cm.) Wide.*	
Inches.	*Millimetres.*	*Inches.*	*Millimetres.*	*Inches.*	*Millimetres.*
·0 to 0·020	0·51	+0·001 −0·002	+0·03 −0·05	±0·002	±0·05
0·021 to 0·030	0·54 to 0·76	+0·002 −0·003	+0·05 −0·08	±0·003	±0·08
0·031 to 0·040	0·79 to 1·02	±0·003	±0·08	±0·003	±0·08
0·041 to 0·050	1·05 to 1·27	±0·003	±0·08	±0·004	±0·10
0·051 to 0·065	1·30 to 1·65	±0·004	±0·10	±0·004	±0·10
0·066 to 0·080	1·68 to 2·03	±0·004	±0·10	±0·005	±0·13
0·801 to 0·100	2·06 to 2·54	±0·006	±0·15	±0·006	±0·15
0·101 to 0·120	2·57 to 3·05	±0·006	±0·15	±0·007	±0·18
0·121 to 0 250	3·08 to 6·35	±0·006	±0·15	±0·008	±0·20

Delivery, Packing, and Shipping.—8. (*a*) Sheets shall be cut to the required dimensions and shall be ordered in as narrow widths as can be used.

(*b*) All sheets shall be oiled for protection against corrosion.

(*c*) Sheets 0·065 inch (1·65 mm.) or thinner shall be boxed, the weight of the box with contents not to exceed 220 pounds (100 kg.).

(*d*) Sheets thicker than 0·065 inch (1·65 mm.), up to and including 0·125 inch (3·18 mm.), shall be crated, the weight of crate and contents not to exceed 220 pounds (100 kg.).

(*e*) Sheets thicker than 0·125 inch (3·18 mm.) may be bundled, the weight of bundle not to exceed 220 pounds (100 kg.)

When electric or crucible furnace steel is specified in the order, the maximum allowable percentages of phosphorus and sulphur may, at the option of the purchaser, be limited to 0·03 per cent.

Manganese Sheet Steel.

Manganese sheet steel containing up to about 1 per cent. of manganese is both tough and ductile; it can be cold bent and worked satisfactorily without exhibiting defects. High manganese steel,* containing from 11 to 14 per cent. of manganese, when suitably quenched from about 950° C. becomes exceedingly tough and non-magnetic; by progressive tempering, the material becomes harder, but more and more magnetic.

This sheet steel, in the commercial form, is very difficult to work, but it can be punched and sheared; in many cases parts may be ground to shape.

When toughened by quenching, high manganese sheet steel can be obtained, with a yield strength of about 20 tons per square inch, and tensile strength of about 35 tons per square inch. It can be bent over double to a very small radius without exhibiting cracks.

Bullet- and Shrapnel-Proof Sheet Steels.

These steels are usually either nickel-chrome† or chrome-vanadium, air, oil, or water hardened; parts made from such materials are stamped, pressed, or otherwise marked in the annealed state, first, and hardened afterwards. Tensile

* Also see p. 384.

† For fuller particulars of these steels, refer to the previous chapter.

strengths varying from 80 to 120 tons per square inch with from 15 to 8 per cent. elongation are obtained after suitably hardening.

These steels are employed for light bullet- and shrapnel-proof parts, such as machine-gun shields, shrapnel-proof infantry helmets, aircraft seats, tanks, and armour, etc.

Bullet-proof plates should have a Brinell hardness of from 300 to 500.

For ordinary Mark VII. nickel pointed lead bullets, a bullet-proof steel plate of 10 S.W.G. (0·128 inch), weighing 5·12 pounds per square foot, will successfully resist penetration at a range of 450 yards. Hardened nickel-chrome steel plates of 12 S.W.G. (0·104 inch), weighing 4·16 pounds per square foot, are bullet-proof at about 500 yards range; plates of 3 S.W.G. (0·252 inch), weighing 10·10 pounds per square foot, are bullet-proof to ordinary pointed bullets at about 500 feet range.

The armour-piercing type of bullet, having a glass-hard alloy steel pointed core, with nickel or copper sheath, will penetrate any of the above plates, but will not perforate, at a range of 500 yards, a nickel-chrome plate of about 4 S.W.G. (0·232 inch), weighing 9·28 pounds per square foot or a plate of 0·34 inch thickness, weighing 13·8 pounds per square foot at 100 yards range.

A type of bullet-proof plate* much used in trench warfare during the late war was 0·376 inch in thickness, and as an inspection test before delivery had to withstand the concentrated fire of the new 0·276 inch bore rifle, which has a much greater penetrating power than the 0·303 inch type.

A bullet proof plate of 8 mm. thickness produced by Messrs W. Beardmore was shown to also be proof against attacks by Mills' bombs, but it was found that the ordinary 7 mm. plates were not capable of stopping the Mauser bullet fired in the reverse way (to give it greater penetrating power), so that it was finally decided to employ a 10 mm. plate.

It has now become possible to produce a special alloy steel

* *The Beardmore News*, February, 1919.

plate of 10 mm. thickness, which will be proof at 60 yards range against either the French or German armour-piercing bullet; this type of plate is eminently suitable for armouring cars, tanks, etc.

The later types of tanks employed, in vital places, armour of 16 mm. thickness.

Electrical Sheet Steels.

Sheet steels* containing a low carbon content are employed for the stampings or punchings of laminated cores of electrical machinery, for magnetic circuits, etc.

Such steels should possess low hysteresis losses, and high permeability, together with non-aging characteristics. It has been found that low carbon steel, containing from 3 to 5 per cent. of silicon, is particularly suitable for transformer sheets on account of its low core losses and high permeability.

Table XCV. gives typical results† for electrical sheets.

Steel Tubing.

There are, at present, three principal classes of steel tubing of the solid, or non-flexible, variety, in everyday use, namely, (*a*) Weldless, or Seamless tubing; (*b*) Welded tubing; and (*c*) Open Seamed or Conduit tubing.

Class (*a*) is produced from a hollow billet by drawing or rolling, and is uniform in structure.

Class (*b*) is made by bending or rolling strips of steel to a circular or any other section and welding the junction. Class (*c*) is made exactly similar to the preceding, but is not welded; it is employed in cases where the tubes are lightly loaded—such as for electric wire conduits, and ornamental purposes.

Seamless tubing can be produced in both carbon and alloy steels, and is of uniform strength, on account of the absence of joints.

* See also p. 397 and 398.

† American Sheet and Tin Plate Company.

TABLE XCV.

PROPERTIES OF ELECTRICAL SHEET STEELS.

Material.	*Ordinary Dynamo and Motor Sheets.*	*Special Dynamo and Motor Sheets.*	*Transformer Sheets.*
	Low Open Hearth Carbon Steel.	*Low Open Hearth Carbon Steel.*	*4 per Cent. Silicon Low Carbon Steel.*
Specific gravity (sheet form)..	7·79	7·72	7·5
Yield point, across grain, pounds per square inch ..	30,000	35,000	29,000
Tensile strength, across grain, pounds per square inch ..	48,000	52,000	96,000
Elongation in 8 inches, across grain, per cent.	21	25	2·4
Yield point, along grain, pounds per square inch ..	33,000	38,000	22,000
Tensile strength, along grain, pounds per square inch ..	55,000	61,000	102,000
Elongation, along grain, per cent.	22	19	2·1
Resistivity, microhm-cm. ..	8 to 12	15 to 18	40 to 50
Hysteresis loss at $\beta = 10{,}000$ ergs per cubic cm. per cycle	4042	3336	1796
Hysteresis coefficient	0·001609	0·001328	0·000715

Welded tubing possesses the advantage that a more uniform wall thickness can be obtained, free from drawing marks, and is not subjected to the disadvantages which often occur in the case of drawing and length rolling processes; it is only possible, however, to employ welding steels such as low and medium carbon, and low nickel steels. The process of manufacturing welded tubing is quicker and less expensive than that of drawing or rolling, but the strength of the welded joint is rather an uncertain quantity; this class of tubing is not employed for aircraft work.

In the case of certain mild steels, the tubing is often first made by welding the rolled plate with an electric arc which can travel along at a uniform rate, and the welded tube is then drawn through dies in the ordinary manner; very satisfactory results are thus obtained, and the method is applicable to non-

ferrous metals, such as brass, but using a brazing process instead of welding.

Manufacture of Seamless Tubing.

The method of manufacturing this class of tubing can best be described by quoting from an interesting paper* upon the subject, given before the Aeronautical Society in 1918, as follows:

"To commence the manufacture of a seamless tube a solid billet of steel, well hammered and rolled, is taken. This billet must be carefully examined for various faults, and any lamination or surface defect removed by chipping, or else the outside of the billet must be turned all over. The usual practice when the latter is done is to turn about $\frac{3}{8}$ inch off the diameter of the billet.

"The first operation is then to pierce a hole. Two ways of doing this are in general use: one is by means of a hydraulic press, similar to the method of piercing shells so common in this country to-day, and the other by means of a rotary piercing machine. The billet, first centred with large shallow holes, is heated to about 1200° C. and fed between rolls having a curved outline and set at an angle which imparts a forward movement to the billet as it is rotated. Great pressure is used (which causes the billet to tend to open along its axis), and the billet is forced against and over a pointed mandril held on the end of a stout rod, which butts against a bracket at a distance of about 7 feet from the centre of the rolls.

"A billet, 4 inches diameter by 24 inches in length, will be made in one operation into a tube about 4 feet to 5 feet long. The pierced billet is then taken to another machine which is provided with upper and lower rolls having semi-circular grooves of various radii, and by a series of operations is rolled into a tube of the required size. The tube is passed over mandrils to give the required thickness.

* "Steel Tubes, Tube Manipulation, and Tubular Structures for Aircraft," by Messrs. W. W. and A. G. Hackett, *Aeronautical Journal*, April, 1918.

"A much quicker process of rolling mild steel tubes is by means of Pilgré rolls; but for high carbon steel or chrome nickel steel this process has been found to be unsuitable.

"COLD DRAWING.

"The first operation in the cold-drawing mills is that of 'tagging'; the hollow bloom (as the rough rolled tube is called) being reduced at one end by suitable semi-circular tools in a power-forging hammer. The tube in the drawing operations to follow will be pulled through the dies by means of the 'tag' thus formed. A small hole is also put into the tube at the point where the tag commences, in order to allow acid and water to work through the tube in the subsequent pickling and swilling processes.

"After being 'tagged' the tube is annealed, pickled in a bath of acid to remove the scale, and then swilled in clean water. Following this, the tube is dried and then immersed in a solution of soap, or in oil, to lubricate it for the drawing operation. It is now ready for drawing.

"There are two methods of cold drawing in general use. One is by drawing down the outside diameter of the tube upon a long bar of uniform diameter and then passing the tube, while on the bar, through rolls fixed in a 'reeling' machine, which is similar to that used in the rotary piercing operation. In carrying out this method the tube is put on to the bar, which must of necessity be smaller than the bore of the tube to be drawn. The tube and the bar are then pulled through a die of hardened steel of such a bore as will give the proper reduction of gauge to the tube.

"The tube is gripped on the 'tag' by means of 'dog' jaws sliding on inclined planes. The 'dog' is moved along the draw-bench by hooks which are dropped into the links of an endless chain. The chains move at a speed of from 12 feet to 35 feet per minute, according to the class of material to be drawn. This process of cold drawing permits of a greater reduction of thickness at each draw than can be obtained by the more usual process of 'plug' drawing, but is rather harsh

on the material, and the expanding of the tubing (already hardened by drawing) to allow the mandril to be extracted sometimes causes splits and fractures. These are more likely to appear if this process is used after the tube has been drawn to a light gauge.

"The second method is that known as 'plug drawing,' and is more usually adopted; in this case a short, hardened mandril is screwed into one end of a long bar. This bar is screwed at the other end into a larger piece of steel known as the 'back sleeve,' which is screwed and fitted with a nut at either end. This sleeve has an axial movement of about 9 inches in the back casting of the draw-bench. The nut at the back is used for the purpose of adjusting the position of the mandril in relation to the die.

"The tube is threaded over the mandril and the 'tag' is passed through the die, which rests against the die plate. Immediately the 'tag' is gripped by the 'dog' it commences to move, the mandril at the same time being drawn forward into position by means of a rope or chain. A reduction in gauge thickness and diameter, with an increase in length is the result, due to the walls of the tube being drawn down between the mandril and the die.

"The usual reduction by this method is about a gauge and a half per draw on low carbon steel. The operation of cold drawing hardens the tube to quite a large extent, and subsequent annealing is necessary.

"ANNEALING.

"A properly annealed tube showing an ultimate tensile stress of about 30 tons per square inch should given about 38 tons after undergoing the drawing operation. To properly prepare the tube for further cold drawing it is therefore necessary to anneal after every drawing operation, which means it has also to be pickled, washed, dried, and lubricated. A hollow bloom 1⅞ inch diameter by 8 inches gauge would require nine or ten 'draws' to make it into a tube 1¼ inch by 22 inches gauge. The annealing is carried out in suitable muffles, usually

at a temperature of about 600° to 650° C., until before the last ' draw,' when a temperature of about 850° C. is advisable. In the case of light gauge tubes, this should be done by ' close annealing, as the scaling and blistering of a light tube by ' open annealing would be fatal.

"When a tube has been drawn to about $\frac{7}{16}$ inch diameter there is great difficulty experienced in drawing on a mandril. The usual practice is to finish $\frac{3}{8}$ inch diameter tubes and smaller by reducing the diameter only. This is termed ' sinking.' The condition of the tube finished in this way is not so good as when finished on a mandril, the strength of the tube being less. From experiments made, tubes from 0·5 per cent. carbon, finished by ' sinking,' show about the same tensile strength as tubes from 0·35 per cent. carbon finished with the usual ' draw ' on the mandril."

Carbon Steel Tubes.

The two most important carbon steels employed for tubing are the mild and medium carbon steels.

Mild steel tubing contains from 0·10 to 0·25 per cent. carbon, whilst the average medium carbon steel content varies from 0·30 to 0·55 per cent.

The usual sizes of tubing commonly employed range from about 3 inches diameter down to $\frac{3}{8}$ inch or $\frac{1}{4}$ inch, and the thicknesses for seamless tubings from about 10 S.W.G. (0·128 inch) down to 24 or 26 S.W.G. (0·022 to 0·018 inch). Carbon steel tubing is widely employed in all branches of engineering work, and in aircraft work for built up and welded fittings, frameworks of control surfaces, and occasionally for gondola, fuselages and body frameworks; it has also been used for airship booms and outriggers, aeroplane leading and trailing edges, wing ribs, and similar objects.

Strength Properties.

The following are the average strength limits for mild steel tubing:

TABLE XCVI.

STRENGTH OF MILD STEEL TUBES.

Material and Condition.	*Yield Point. Tons per Square Inch.*	*Tensile Strength. Tons per Square Inch.*
Mild steel tube (annealed)	18 to 22	30 to 36
Mild steel tube (as drawn)	24 to 30	33 to 40

The tensile strength of tubes of the same billet material is greater for the smaller diameter tubings, due to the greater hardening effect due to rolling; the variation in strength between a 2-inch and a ⅜-inch tube may exceed 25 per cent., when reckoned upon that of the larger tube.

The following results* of tension tests refer to steel tubing containing 0·35 per cent. of carbon and 0·65 per cent. of manganese. It will be observed that the average strength and elongation are less for the thinner tubing; in general when the tubing thickness is reduced below about one-twentieth of the external diameter, the strength is reduced in proportion to the thickness.

TABLE XCVII.

TENSILE STRENGTH OF CARBON STEEL TUBING.

Diameter in Inches.	*Thickness of Wall. Inches.*	*Yield Point. Tons per Square Inch.*	*Tensile Strength. Tons per Square Inch.*	*Elongation per Cent. in 8 Inches.*
1·180	0·031	32·6	38·0	15·6
1·180	0·031	36·8	40·6	15·8
0·986	0·019	32·8	43·4	13·8
0·986	0·019	31·0	36·3	13·4
0·984	0·019	33·0	36·7	12·9
0·986	0·019	31·4	37·8	15·5

Crushing Test.

It is now general to specify a *crushing test* for mild steel tubing—namely, that the specimen to be tested, of length

* Columbia University Testing Laboratory.

equal to $1\frac{1}{2}$ times the outside diameter, should withstand endwise crushing until its length is decreased by from $\frac{1}{3}$ to $\frac{1}{2}$ of its original value, or until the outside diameter is increased in one zone by 25 per cent., or until one complete fold is formed, without splitting or cracking.

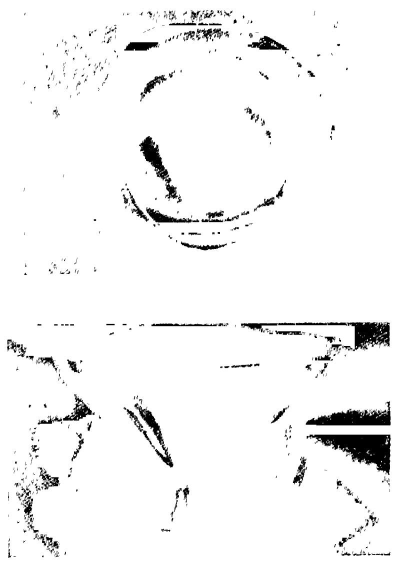


FIG. 178.—THE CRUSHING OF STEEL AND IRON TUBING.

Fig. 178 shows the results of an endwise crushing test* made upon an electrolytic iron tube; it will be seen that this material, like good mild steel, will withstand considerable distortion without cracking.

Straightness, Diameter and Wall Thickness Variations.

Tubing is usually supplied in lengths of from 14 to 16 feet, and, apart from sagging effects due to its weight, should be specified to be straight to within 1 in 600. The difficulties of annealing and heat-treating long lengths of tubing which in the

* *Engineering.*

ordinary way would necessitate subsequent restraightening have been satisfactorily overcome* by clamping the tube firmly in a vertical position between electric terminals. When a current is passed through the tube it is heated to the correct temperature for the material, and the tube is then automatically released by the terminals, when it drops into a vertical cylinder containing the quenching liquid. This method, which can be applied to both carbon and alloy steels, does not necessitate restraightening. The permissible variation in the outside diameter of seamless tubing is usually stipulated as being $\pm 0{\cdot}003$ inch for tubes under $1\frac{1}{2}$ inches outside diameter, and $\pm 0{\cdot}005$ inch for those over $1\frac{1}{2}$ inches.

The wall thickness should not vary more than $+8$ per cent. or -3 per cent.

International Aircraft Standard Specifications.

(A) Specifications for Welded Steel Tubes.

General.—1. The general specifications 1G1 shall form, according to their applicability, a part of these specifications.

Use.—2. These tubes are suitable only for unstressed parts, such as conduit tubes.

Material.—3. The I.A.S.B. standard steel, No. 1020, shall be used. Its composition is as follows

Carbon	0·15 to 0·25 per cent.
Manganese	0·30 to 0·60 ,,
Phosphorus (max.)	0·045 ,,
Sulphur (max.)	0·050 ,,

Manufacture.—4. All tubes shall be of the welded type. They must be carefully annealed before the final pass.

Any tube may be rejected at any time because of injurious defects or faults in the steel which are revealed by manufacturing operations, notwithstanding the fact that it has previously passed inspection. Such rejected material shall be returned to the manufacturer at the latter's expense. This clause shall not apply to materials fabricated after export.

Workmanship and Finish.—5. The tubes are to be smooth, of the section specified, and within the permissible tolerances as to wall thickness of uniform diameter, free from scale, dirt, specks, longitudinal seaming, lamination, grooving, and blistering, both internally and externally.

Physical Properties and Tests.—6. The tubes shall have the following physical properties

Crushing Test.—One test specimen from every 100 feet (30·5 m.) of tubing is to be crushed endwise until the outside diameter is increased in

* Snead's Process.

one zone by 25 per cent., or until one complete fold is formed. The specimen shall stand this treatment without cracking.

Whenever possible the selection of test specimens shall be made by heats.

The specimens for the crushing tests shall have a length of 1·5 times the diameter of the tube.

DIMENSIONS AND TOLERANCES.—7 (*a*). The following tolerances will be allowed on the outside diameter of tubes

Tubes under 1·5 inches (38·1 mm.) diameter, ± 0·005 inch (0·13 mm.).
Tubes over 1·5 inches (38·1 mm.) diameter, ± 0·010 inch (0·25 mm.).

(*b*) The variation in wall thickness may be ± 10 per cent. of the dimension specified.

(*c*) In no part of any tube shall the departure from straightness exceed 1 in 600.

DELIVERY, PACKING, AND SHIPPING.—8. All tubes shall be well oiled and delivered in boxes not exceeding 220 pounds (100 kg.) gross weight.

(B) SPECIFICATIONS FOR MILD CARBON-STEEL TUBES.

GENERAL.—1. The general specifications 1G1 shall form, according to their applicability, a part of these specifications.

USE.—2. These tubes are suitable for all parts not heavily stressed, such as trailing edges and elevators.

MATERIAL.—3. The I.A.S.B. standard steel No. 1020 shall be used The composition is as follows.

Carbon	0·15 to 0·25 per cent.
Manganese	0·30 to 0·60 ,,
Phosphorus (max.)	0·045 ,,
Sulphur (max.)	0·050 ,,

MANUFACTURE.—4. The tubes are to be of the cold-drawn, seamless type and are to be furnished annealed.

Any tube may be rejected at any time because of injurious defects or faults in the steel which are revealed by manufacturing operations, notwithstanding the fact that it has previously passed inspection. Such rejected material shall be returned to the manufacturer at the latter's expense. This clause shall not apply to materials fabricated after export.

WORKMANSHIP AND FINISH.—5. The tubes are to be smooth, of the section specified, and within the permissible tolerances as to wall thickness of uniform diameter, free from scale, dirt, specks, longitudinal seaming, lamination, grooving, and blistering, both internally and externally.

PHYSICAL PROPERTIES AND TESTS.—6. The tubes shall have the following physical properties·

TENSILE TEST.—(*a*)

Minimum tensile strength, 60,000 pounds per square inch (42·18 kg./mm.^{2}).
Minimum yield point, 36,000 pounds per square inch (25·31 kg./mm.^{2}).
Minimum elongation, 25 per cent. in 2 inches (50·8 mm.) or 10 per cent. in 8 inches (203·2 mm.).

CRUSHING TEST.—(*b*) The test specimen shall be crushed endwise until the outside diameter is increased in one zone by 25 per cent., or until one complete fold is formed. The specimen shall stand this treatment without cracking.

SELECTION OF TEST SPECIMENS.—7. One test specimen for the tensile test shall be chosen from every 400 feet (121·9 m.) of tubing and one test specimen for the crushing test from every 100 feet (30·5 m.) of tubing.

The specimens for the crushing tests shall have a length of 1·5 times the diameter of the tube.

Whenever possible the selection of test specimens shall be made by heats.

DIMENSIONS AND TOLERANCES.—8. (*a*) The following tolerances will be allowed on the outside diameter of tubes

Tubes under 1·5 inches (38·1 mm.) diameter, $\pm$ 0·003 inch (0·08 mm.)
Tubes over 1·5 inches (38·1 mm.) diameter, $\pm$ 0·005 inch (0·13 mm.).

The manufacturer and purchaser shall agree upon tolerances for coulissant or telescoping tubes.

(*b*) The variation in wall thickness may be $\pm$ 10 per cent. of the dimensions specified.

(*c*) In no part of any tube shall the departure from straightness exceed 1 in 600.

DELIVERY, PACKING, AND SHIPPING.—9. All tubes shall be well oiled and delivered in boxes not exceeding 220 pounds (100 kg.) gross weight.

Alloy Steel Tubes.

Apart from the use of high carbon steel, it is now common to employ alloy steels such as low nickel (3 to 5 per cent.) and nickel-chrome steels.

These steels require greater care in their manufacture and subsequent heat treatment; the tubes are produced by the "plug" drawing process, but the mandrils and dies wear out much more rapidly than in the case of carbon steels. Very careful annealing is also necessary. The amount of reduction in the gauge, or thickness, is only about one-half of that obtainable in the case of mild steel. Nickel steel containing about $3\frac{1}{2}$ per cent. of nickel is much used in America for tubing In Table XCVIII. the results given are typical of the properties of nickel steel tubes of different thicknesses.

Wall Thickness and Strength.

The results of these tests show that thin-walled tubes do not develop the maximum strength values of the material, when the wall thickness is less than 5 per cent. of the wall diameter.

TABLE XCVIII.

PROPERTIES OF 3½ PER CENT. NICKEL STEEL TUBES.

(A) TRANSVERSE BENDING AND TENSILE TESTS.

Specimen No.	Transverse Bending. Fibre Stress at Elastic Limit. Tons per Square Inch.	Transverse Bending. Maximum Fibre Stress. Tons per Square Inch.	Tension. Fibre Stress at Elastic Limit. Tons per Square Inch.	Tension. Maximum Fibre Stress. Tons per Square Inch.
1	20·6	30·5	25·7	37·2
2	30·8	56·9	30·5	46·0
3	38·3	57·2	36·0	44·9
4	34·8	60·8	34·2	52·1
5A	42·1	62·3	33·8	52·4

(B) TORSION TEST.

Specimen No.	Tube Diameter. Inches.	Thickness of Walls. Inches.	Fibre Stress at Elastic Limit. Tons per Square Inch.	Maximum Fibre Stress. Tons per Square Inch.	Modulus of Rigidity. Tons per Square Inch.
1	1·180	0·022	—	17·3	4420
2	1·180	0·040	17·5	23·6	5180
3	1·182	0·061	18·3	27·3	5230
4	1·184	0·076	22·2	33·0	4910
5A	1·185	0·096	19·4	33·8	5310

Thin-walled tubes, which should from purely theoretical considerations give the maximum strength for weight, are not practically feasible, owing to the preceding effects, and to the fact that they are liable to local deformation or buckling, and that the relative effect of corrosion or rusting is much greater.

Thin-walled struts* and beams invariably fail by local buckling or secondary flexure, at a lower value of the breaking stress than for the solid material or for thicker tubes.

Nickel-Chrome Steel Tubes.

The manufacturing difficulties are much greater in the case of these tubes, and the annealing and heat treatment require special care.

* Also *vide* p. 59.

Nickel-chrome steel tubes are employed in aircraft work for undercarriage axles and struts, rudder posts, and similar parts.

The following is a typical analysis* of a nickel-chrome steel tube.

Carbon	0·30 per cent.
Silicon	0·16 ,,
Sulphur	0·03 ,,
Phosphorus	0·03 ,,
Manganese	0·45 ,,
Nickel	1·10 ,,
Chromium	4·00 ,,

The tensile strength of this material in the annealed state is about 45 tons per square inch, with about 15 per cent. elongation in 2 inches; in the air-hardened state the elastic limit is about 70 tons per square inch, and the tensile strength from 90 to 100 tons per square inch, with from 8 to 5 per cent. elongation in 2 inches. It is stated that it is inadvisable to use sulphuric or muriatic acids for cleaning the scale off hardened tubes, as it makes the material brittle.

Crushing Test.

It is usual to specify a crushing test upon annealed high tensile tubing, namely, that a section of the tubing of length equal to 1½ times the outside diameter shall withstand crushing endwise until its length is one-half of the initial length, without exhibiting cracks or splits on the outside surface.

Tolerances.

High tensile steel tubes should be straight to within 1 part in 600.

It is usual to specify the outside diameter limits to be within ±0·005 inch, whilst the thickness should not be greater than the nominal value by more than 10 per cent., or below by less than 5 per cent.

International Aircraft Standard Specifications.

SPECIFICATION FOR ALLOY STEEL TUBES.

GENERAL.—1. The general specifications 1G1 shall form, according to their applicability, a part of these specifications.

* Messrs. Accles and Pollock, Oldbury.

USE.—2. These tubes are suitable for axles and parts subject to shock.

MATERIAL.—3. The material for these tubes shall be chosen from the I.A.S.B. standard steels listed below. The composition chosen shall be stated by the manufacturer and is further limited as follows· Carbon, not over 0·35 per cent.

MANUFACTURE.—4. (*a*) The tubes are to be of the cold-drawn, seamless type. To avoid overhardening after annealing the tube wall shall not be reduced more than 20 per cent. in thickness in the final passes.

HEAT TREATMENT.—(*b*) The tubes shall be heat-treated to temper 1 or 2 as ordered. The quenching is to be done in oil.

(*c*) Any tube may be rejected at any time because of injurious defects or faults in the steel which are revealed by manufacturing operations, notwithstanding the fact that it has previously passed inspection. Such rejected material shall be returned to the manufacturer at the latter's expense. This clause shall not apply to materials fabricated after export.

WORKMANSHIP AND FINISH.—5. The tubes are to be smooth, of the section specified, and within the permissible tolerances as to wall thickness of uniform diameter, free from scale, dirt, specks, longitudinal seaming, lamination, grooving, and blistering, both internally and externally.

PHYSICAL PROPERTIES AND TESTS.—6. The tubes shall have the following physical properties.

TENSILE TEST.—(*a*).

TEMPER I.

Minimum tensile strength, 110,000 pounds per square inch (77·33 kg./mm.^{2}).
Minimum yield point, 90,000 pounds per square inch (63·27 kg./mm.^{2}).
Minimum elongation, 15 per cent. in 2 inches (50·8 mm.) or 5 per cent. in 8 inches (203·2 mm.).

TEMPER II.

Minimum ultimate strength, 85,000 pounds per square inch (59·76 kg./mm.^{2}).
Minimum yield point, 60,000 pounds per square inch (42·18 kg./mm.^{2}).
Minimum elongation; 25 per cent. in 2 inches (50·8 mm.) or 10 per cent. in 8 inches (203·2 mm.).

CRUSHING TEST.—(*b*) The test specimen shall be crushed endwise until the outside diameter is increased in one zone by 25 per cent., or until one complete fold is formed. The specimen must stand this treatment without cracking.

SELECTION OF TEST SPECIMENS.—7. One test specimen for the tensile test shall be chosen from every 400 feet (121·9 m.) of tubing and one test specimen for the crushing test from every 100 feet (30·5 m.) of tubing.

The specimens for the crushing tests shall have a length of 1·5 times the diameter of the tube.

Whenever possible the selection of test specimens shall be made by heats.

DIMENSIONS AND TOLERANCES.—8. (*a*) The following tolerances will be allowed on the outside diameter of tubes:

Tubes under 1·5 inches (38·1 mm.) diameter, ± 0·003 inch (0·08 mm.).
Tubes over 1·5 inches (38·1 mm.) diameter, ± 0·005 inch (0·13 mm.).

The manufacturer and purchaser shall agree upon tolerances for coulissant or telescoping tubes.

(*b*) The variation in wall thickness may be ± 10 per cent. of the dimensions specified.

(*c*) In no part of any tube shall the departure from straightness exceed 1 in 600.

Delivery, Packing, and Shipping.—9. All tubes shall be well oiled and delivered in boxes not exceeding 220 pounds (100 kg.) gross weight.

When electric or crucible furnace steel is specified in the order, the maximum allowable percentages of phosphorus and sulphur may, at the option of the purchaser, be limited to 0·03 per cent.

TABLE XCIX.

Chemical Composition of Standard Alloy Steels.

Nickel Steels.

No.	*Carbon.*	*Manganese.*	*Phosphorus (max.).*	*Sulphur (max.).*	*Nickel.*	*Chromium.*
2320	0·15 to 0·25	0·30 to 0·60	0·040	0·045	3·25 to 3·75	—
2325	0·20 to 0·30	0·50 to 0·80	0·040	0·045	3·25 to 3·75	—
2330	0·25 to 0·35	0·50 to 0·80	0·040	0·045	3·25 to 3·75	—

Chromium-Vanadium Steels.

No.	*Carbon.*	*Manganese.*	*Phosphorus (max.).*	*Sulphur (max.).*	*Chromium.*	*Vanadium (min.).*
6120	0·15 to 0·25	0·30 to 0·60	0·040	0·045	0·60 to 0·90	0·15
6130	0·25 to 0·35	0·50 to 0·80	0·040	0·045	0·80 to 1·10	0·15

Facts Concerning the Strength of Steel Tubing.

The properties of steel tubing under alternating stress conditions can be investigated by means of a machine resembling the Wöhler type,* whilst for shock tests the falling weight impact type of machine is convenient.

The results of a series of tests† made upon steel tubing and tube sockets and liners may be briefly enumerated as follows:

* See Fig. 104, p. 212. † Footnote, p. 411.

1. The effect of drilling a small hole in a tube, which is alternately stressed nearly up to its elastic limit, is to considerably weaken the tube; the undrilled tube is stated to have from 10 to 20 times the life of the drilled tube. Where drilling is necessary, the tube should be properly reinforced with a liner or sleeve. Hard tubing is affected to a much more marked extent than annealed tubing.

2. Lugs intended for connecting pieces of tubing with brackets, fittings, or other members, whether of the sleeve or liner type, should be tapered off towards the outlet, as

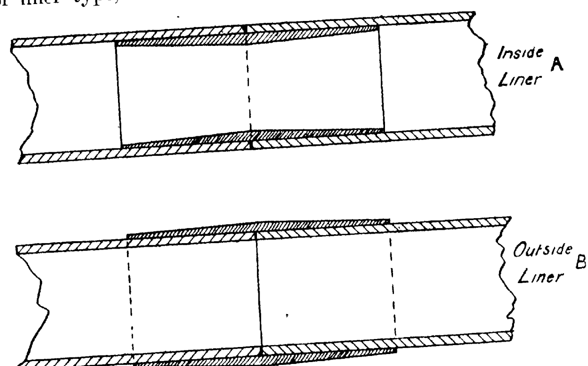


FIG. 179.—LINERS FOR TUBULAR JOINTS.

shown in Fig. 179. If left parallel, there is a serious weakening due to the abrupt change of section, together with want of resilience at the socket portion.

3. For beams of the cantilever type, tapered tubes are preferable to uniform ones, owing to their greater resilience and lighter weight for the same strength. Alternating tests made on a Wöhler type of machine, at 400 r.p.m., on 1 inch by 20 S.W.G. (0·036 inch) steel tubing, proved that whereas two parallel tubings broke at 20,585 and 30,390 revolutions respectively, yet when tapered tubes, tapering by ½ inch per foot, were employed, of the same thickness, they broke at 23,557 and 38,225 revolutions respectively.

Each of the tubes was loaded with 111·56 pounds at a

distance of 12·75 inches from the grips, which was equivalent to a stress of about 25 tons per square inch.

Tapering in thickness, as distinct from tapering in diameter, has been shown to be both economical and beneficial. An instance of this is in the case of motor-cycle front-forks, which, when made from 19 S.W.G. tubing, invariably broke off where they were brazed to the crown. Increasing the thickness to 18 and 17 S.W.G. respectively, failed to prevent these breakages. When, however, tubes tapering from 19 S.W.G. at the crown to 22 S.W.G. at the bottom ends were employed, the trouble was completely overcome; the increased resilience no doubt accounted for this effect.

4. Tubular liners should preferably be soft soldered in place, and should not be of too great a thickness compared with that of the tube that they are intended to reinforce. Liners tapering down to a minimum thickness at their outer ends are more satisfactory than parallel liners. Tapered sleeves are equally satisfactory; in both cases the outer end thickness should be less than that of the tube itself. Sleeves or liners which are merely pressed into position are not satisfactory; soldering or brazing should be resorted to in every case. Tests made upon similar 1 inch by 20 S.W.G. tubes—(*a*) drilled, but without a sleeve; (*b*) drilled, but with a sleeve pressed on; and (*c*) drilled, but with a similar sleeve soldered on, the sleeves in each case being $2\frac{1}{2}$ inches long by 18 S.W.G., and placed over the holes—gave the following results:

(*a*) Plain drilled tube	3684	revolutions	before fracture.
(*b*) Pulled tube, with pressed sleeve	9320	,,	,,
(*c*) Pulled tube, with soldered sleeve	48,687	,,	,,

5. Where sockets are employed, the tube should be either brazed or pinned and soldered.* The results of tests upon soldered joints show that there should be about 0·005 inch clearance between the tube and socket diameters, as a maximum value, and that smaller clearances give as good results. The shearing stress of a good soldered joint may be taken as being about $2\frac{1}{2}$ tons per superficial inch. With a soldered

* Soft and silver-soldered tubular joints are much used in aircraft work.

socket joint it is an easy matter to make the tensile strength of the joint at least equal to that of the tube.

6. For tubular members under stress soft soldering is recommended in preference to brazing or welding, as the temperatures of the process are low enough not to affect the hardness of the metal, especially in the case of alloy and hard drawn steel tubes.

Hard soldering, or silver soldering, gives a stronger joint, and the temperature of the operation is lower than for brazing, but much higher than for soft soldering. Brazing is not recommended for tubular structures which have to take stresses, or for medium thicknesses of tubes. It is, however, applicable to tubes of appreciable wall-thickness which have to take torsional stresses through the joint. Cardan shafts are often built up of a long tube, with the universal joint pin sockets brazed in each end, and to the author's knowledge have given every satisfaction. Brazing, however, is not recommended for aircraft work, generally speaking.

Welding is even less to be recommended for any members upon automobiles or aircraft in which stresses are transmitted through the joints; welded tubular work is employed to some extent in the case of strut sockets in which the function of the weld is merely to hold the tubular position *in situ*, and only to take light stresses. All welded work, which in aircraft practice is of a "locative" nature, should be annealed subsequent to welding.

Fig. 180 shows in section a tubular bicycle-frame made by Messrs. Accles and Pollock; the various lugs, tapered tubes, and fittings shown serve to illustrate the points previously mentioned.

Section Tubing.

Most of the foregoing remarks have been confined to circular tubing, but by far the greater quantity of tubing employed in aircraft work is of the sectional form.

Section tubing is made from seamless circular tubing by three different processes, namely, by drawing, rolling, and

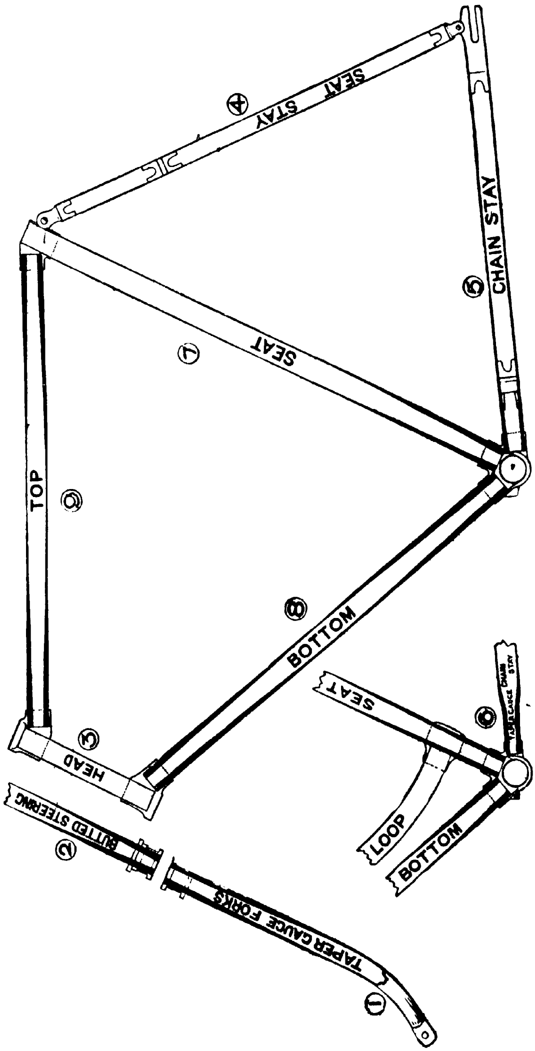


Fig. 180.—Showing Tapered Tubing, Lugs, and Brackets.

pressing; when made by the latter process, only short lengths can be dealt with. In the drawing process there is a slight reduction in the periphery from the round to the sectional shape, but in the rolling or pressing processes it remains unaltered.

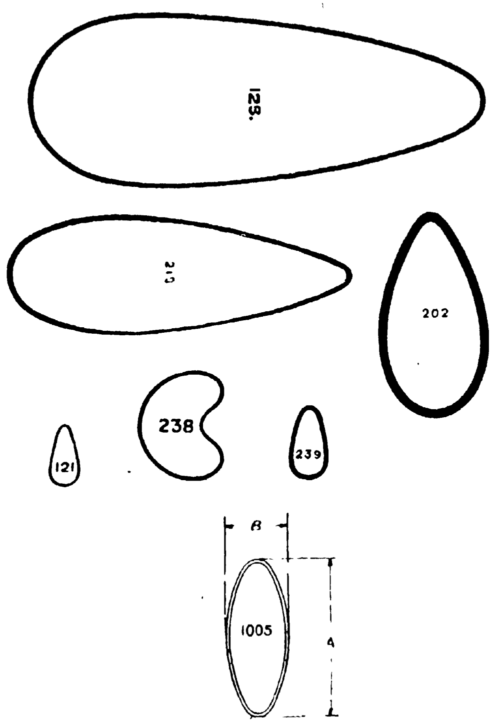


FIG. 181.—SECTION TUBING USED IN AIRCRAFT CONSTRUCTION.

The section of tubing, made from round tubing, should be so designed that there is no straight portion or sides anywhere, that is to say, the whole contour should be everywhere curved; this reduces the difficulty of manufacture. Section tubing, especially of the "streamline" form, is often made from flat strips, bent over a former, and seam-welded at

the junction of the edges, as shown in Fig. 182. This diagram* also shows some typical sections and reinforced tubes employed in aircraft and automobile work.

The diagrams shown in Fig. 181 refer to aircraft section tubing, the streamline shapes shown in sections 125, 210, and

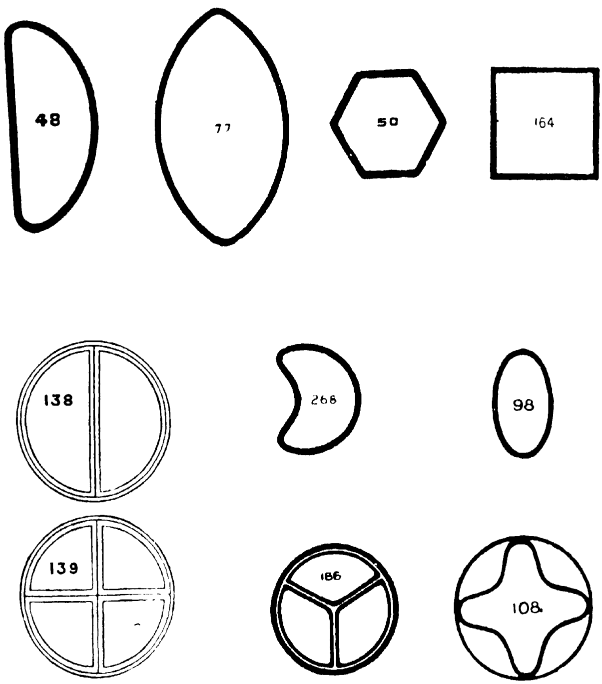


Fig. 181a.—Showing Reinforced Tube Sections.

202 being suitable for exposed members under strut action.

Sections 121, 238, and 239 are suitable for the leading and trailing edges of wings and control surfaces.

The standard aircraft sections adopted for many purposes in this country are similar to that shown in section 1005, and the principal sizes and dimensions employed are given in the following table:

* Messrs. Accles and Pollock's sections.

TABLE C.

DIMENSIONS OF AIRCRAFT ELLIPTIC TUBES.

Section No.	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010
Dimensions A	0·500	0·625	0·750	1·000	1·250	1·500	1·750	2·000	2·250	2·500
Dimensions B	0·245	0·250	0·300	0·400	0·500	0·600	0·700	0·800	0·900	1·000
Equivalent Circular Diameter	$\frac{13}{32}$	$\frac{15}{32}$	$\frac{9}{16}$	$\frac{3}{4}$	$\frac{15}{16}$	$1\frac{1}{8}$	$1\frac{5}{16}$	$1\frac{15}{32}$	$1\frac{21}{32}$	$1\frac{7}{8}$

Note.—All dimensions are given in inches.

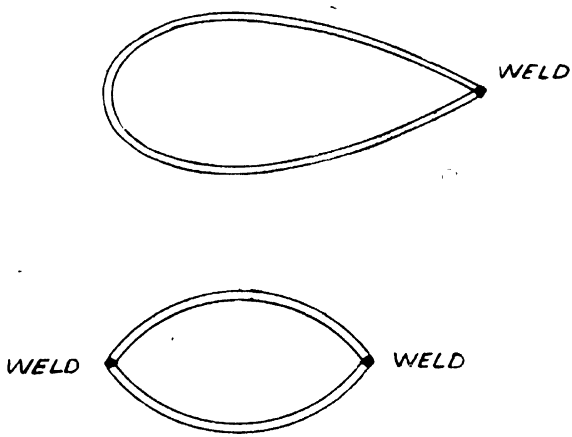


FIG. 182.—BUILT-UP SECTION TUBING

A series of telescopic sections is also employed for use as liners and sockets with most of the above sizes of tubes.

Hollow Bars.

Bars of any section can now be made having a circular hole of any diameter right through; the expense and difficulties in the way of drilling long lengths of bar or rod are thus avoided.

It is now possible to produce a $\frac{3}{4}$-inch diameter bar with a $\frac{1}{4}$-inch hole through it in lengths up to 15 feet.

TABLE CI.

WEIGHTS OF COLD DRAWN WELDLESS STEEL TUBING. (Weights in pounds per foot.)

Outside Diameter.		$\frac{3}{8}$ *Inch.*	$\frac{1}{2}$ *Inch.*	$\frac{5}{8}$ *Inch.*	$\frac{3}{4}$ *Inch.*	$\frac{7}{8}$ *Inch.*	1 *Inch.*	$1\frac{1}{8}$ *Inches.*	$1\frac{1}{4}$ *Inches.*	$1\frac{3}{8}$ *Inches.*	$1\frac{1}{2}$ *Inches.*	$1\frac{5}{8}$ *Inches.*	$1\frac{3}{4}$ *Inches.*	$1\frac{7}{8}$ *Inches.*	2 *Inches.*
Thickness.															
No. S.W.G.	*Decimals of an Inch.*	0·375	0·500	0·625	0·750	0·875	1·000	1·125	1·250	1·375	1·500	1·625	1·750	1·875	2·000
24	0·022	0·082	0·111	0·140	0·169	0·198	0·228	0·257	0·286	0·318	0·349	0·376	0·406	0·435	0·466
23	0·024	0·093	0·126	0·159	0·192	0·225	0·258	0·291	0·324	0·346	0·379	0·410	0·440	0·474	0·506
22	0·028	0·103	0·140	0·177	0·214	0·251	0·288	0·325	0·362	0·403	0·440	0·477	0·515	0·552	0·589
21	0·032	0·116	0·159	0·201	0·243	0·285	0·328	0·370	0·413	0·459	0·492	0·544	0·587	0·630	0·672
20	0·036	0·126	0·172	0·219	0·265	0·311	0·358	0·404	0·450	0·515	0·563	0·644	0·659	0·707	0·755
19	0·040	0·148	0·204	0·259	0·315	0·370	0·426	0·482	0·537	0·570	0·624	0·677	0·720	0·784	0·837
18	0·048	0·169	0·234	0·299	0·364	0·428	0·493	0·558	0·623	0·688	0·747	0·808	0·872	0·936	1·000
17	0·056	0·195	0·272	0·348	0·425	0·501	0·578	0·655	0·732	0·808	0·885	0·962	1·039	1·115	1·192
16	0·064	0·213	0·300	0·385	0·471	0·557	0·643	0·729	0·815	0·901	0·987	1·073	1·159	1·245	1·331
15	0·072	0·231	0·326	0·422	0·517	0·612	0·707	0·803	0·898	0·993	1·088	1·184	1·279	1·375	1·470
14	0·080	0·257	0·367	0·476	0·586	0·696	0·806	0·916	1·025	1·135	1·245	1·355	1·465	1·575	1·685
13	0·092	0·282	0·407	0·533	0·659	0·785	0·910	1·036	1·162	1·287	1·413	1·539	1·664	1·790	1·916
12	0·104	0·307	0·451	0·595	0·740	0·884	1·028	1·172	1·317	1·461	1·605	1·749	1·894	2·038	2·182
11	0·116	0·324	0·483	0·642	0·800	0·959	0·118	1·277	1·436	1·594	1·753	1·912	2·071	2·230	2·389
10	0·128	0·342	0·519	0·697	0·874	1·051	1·229	1·406	1·549	1·723	1·896	2·069	2·239	2·409	2·587

The process* consists in taking a bloom, or billet, of a length varying from 12 to 20 inches, and drilling through it a hole of such a size that it will subsequently roll down to the required size. The hole is then tightly packed with a material of special composition, and the ends of the hole are plugged. The billet is then heated and rolled in a rolling mill until the external dimensions of the desired amount are obtained. In order to remove the core, or packing material, hydraulic pressure is applied when the plugs are removed. The process may be employed for most kinds of steel and for any bar section, such as square, hexagonal (for making nuts), or octagonal, and the location or centrality of the hole is sufficiently accurate for most purposes.

Flexible Metallic Tubing.

Metallic tubing, which is gas, oil, and petrol tight, can be made in iron, steel, copper, brass, and other metals in such a manner that it is as flexible as an india-rubber hose-pipe of the same size.

The advantages of this tubing over rubber tubing are that it can be made ever so much stronger, it will withstand the action of oil, gas, and other influences, and is more permanent.

It can be produced in diameters up to 8 inches, and will withstand steam pressures up to 300 pounds per square inch satisfactorily, and gas or hydraulic pressures up to 3000 pounds per square inch.†

This tubing, which is employed for petrol and gas engine exhaust pipes, and upon motor cars and cycles, aircraft engines, etc., successfully withstands the corrosive action, heat, and pressures of the exhaust gases.

Manufacture.

The tubing is made up of a series of interlocked spiral ribbons of metal, which are in their turn made from thin strips of the metal. Each strip is passed through a graduated set

* Messrs. Dunford and Elliott, Sheffield.

† Pressures up to 5000 pounds per square inch have been used for test purposes.

of rolls, having the desired profile to be imparted to the strip; these profiles vary according to the purpose of the tubing.

The type of flexible tubing* illustrated in Fig. 183, and which is widely employed for internal pressure purposes, is made up of a series of spiral ribbons each having the double-hook form of section shown; the consecutive ribbons are wound upon each other, in turn, on a mandril, so that each one grips the preceding one. The circular cavity, which is provided at the flat extremity

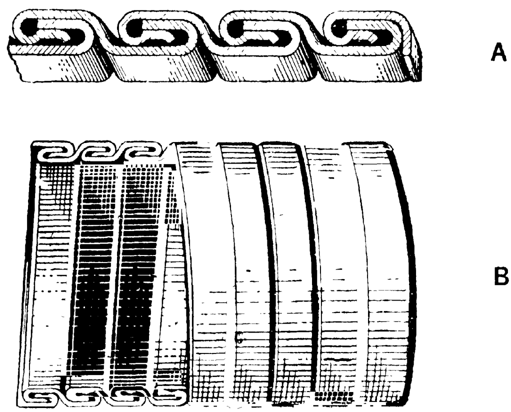


FIG. 183.—SECTION OF FLEXIBLE TUBING.

of the interior hook, is filled either with rubber or asbestos, which is wound on, along with the corrugated metal ribbon, in the form of a thread or string.

The degree of flexibility of the finished tubing depends mainly on the amount of play possible between each successive strand, and as there is a limit to this amount, the successive metal strips become rigid after a certain degree of bending; in this manner the buckling or kinking which occurs with solid tubes is avoided.

The diameter of the smallest circle into which a flexible metallic tube can be bent is about 16 times the diameter of

* Manufactured by the United Flexible Metallic Tubing Co., London.

the tube itself for pipes of from ½ to 2 inches diameter, and about 10 times for 10-inch pipes.

The material employed for the strongest metallic tubings is galvanized, nickeled, or metal-coated Swedish iron or low carbon steel.

For water and gas joints rubber packing between the metal strips is usually employed, except in the case of copper tubing, in which the rubber is speedily attacked.

For oil, petrol, steam, and exhaust gases it is usual to employ asbestos packing.

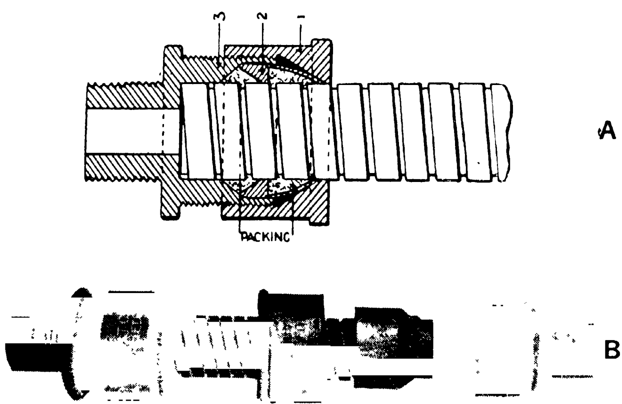


FIG. 184.—LOW PRESSURE FLEXIBLE TUBING CONNEXIONS.

Method of Making Joints and Connexions.

For ordinary low-pressure gases, such as domestic illuminating gas, connexions between tubes or fittings can be made by means of a simple moulded rubber tube, which slips over the parts to be joined.

A more permanent metal joint for gas is shown in Fig. 184, and simply consists of male and female milled screws, which can be pushed over the flexible tubing, with packing in between, and screwed up by hand.

A large variety of designs of connexions are employed for

flexible metallic tubing, including complicated screwed gun-metal high-pressure flanged couplings, ordinary hexagonal unions, hose-pipe connexions, etc.

In cases where high pressures occur, a special nut is provided for anchoring one of the connexion members, which

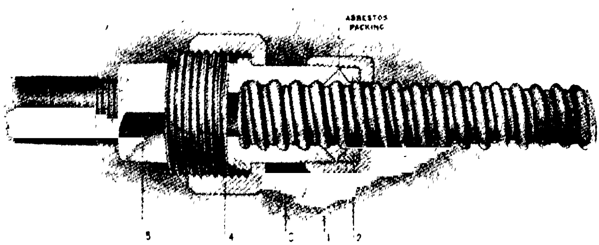


FIG. 185.—HIGH-PRESSURE FLEXIBLE TUBING CONNEXIONS.

screws directly on to the flexible tubing itself, as shown in Fig. 185.

For low gas pressure work coned fittings are employed with white-lead and asbestos packing.

Applications.

In aeronautical work flexible metallic tubing of the zinc, coated iron or steel class is employed for oil pipes, from the oil tank to the engine, for exhaust pipes,* and for speaking-tubes for it has been found that the spiral grooves inside the tubing are not detrimental to the travel of sound waves. It has also been employed for air-ducts to carburettors, etc.

Incidentally it may be mentioned that flexible metallic tubing is employed for petroleum pipe lines, steam connexions between railway carriages, for hot climatic conditions where rubber would rapidly perish, for salvage pumps, compressed air lines for pneumatic tools and rock drills, fire-engine pumps, and in numerous other instances.

* The expense and difficulties of complex bends in solid tubing are thus avoided.

Steel and Iron Wire.

Wire is made by the repeated process of drawing a rod of the material through a series of hard steel dies; for example, a steel rod of $\frac{1}{4}$-inch diameter (or about 3 S.W.G.) can be drawn through tungsten steel dies so that it is reduced by about one gauge (S.W.G.) number at each draw, until its final diameter is about 0·040 inch (or 19 S.W.G.).

Hardening due to Drawing.

During the process of drawing the material becomes progressively harder and less ductile; for example, the tensile strength of a certain steel wire of 0·126 inch (about 10 S.W.G.) was found to be 88 tons per square inch with 2 per cent. extension, whilst that of the same material wire of 0·040 inch (19 S.W.G.) was 125 tons per square inch with only 0·3 per cent. extension.

The torsional strengths of the two wires were such that the thicker wire required 13·3 complete twists to break it, for a length of 5 inches, whilst the thinner wire required 35·6 twists in the same length.

Fig. 186 shows how the tensile strength of plough steel aircraft wire varies with the amount of drawing—that is, with the gauge or diameter of wire.

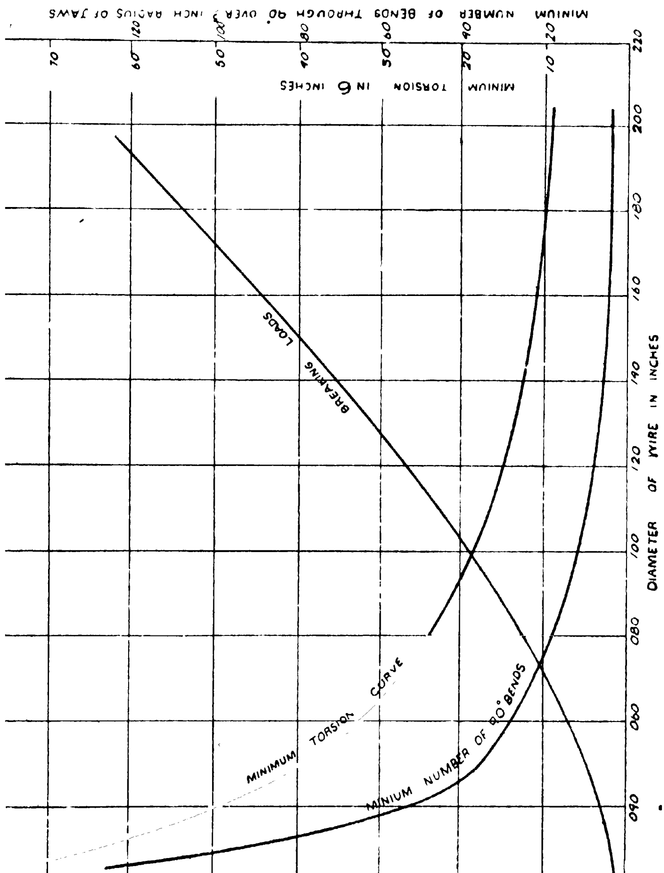
The same diagram also shows the number of complete twists required to break wires of different diameters, and the number of bends,* through angles of 90°, which the wires will withstand before fracturing.

Microscopical examination† of the internal structure of drawn steel wire has shown that it is desirable to obtain both pearlite and sorbite, and that the more sorbite present the tougher and stronger will be the wire; in attempting to obtain the maximum of sorbite there is, however, a risk of obtaining martensite and troosite, which tend to cause the wire to fracture during the drawing process.

* For particulars of wire bending tests, see p. 441.

† *Vide* p. 147, "The Microscopic Examination of Metals," F. Osmond and J. E. Stead.

Too rapid chilling after leaving the patenting furnace will promote the formation of sorbite and martensite; another cause of the presence of the latter constituents is that due to



the frictional heat, during service or drawing, which causes the surface layers to be momentarily heated to redness, usually followed by a chilling effect, which leaves the surface layers

in the martensitic condition, and causes the wire to break when bent.

The failure of wire ropes is often due to this cause.

Another source of failure is that due to the use of badly designed pulleys, in which the surface of the crown wires spreads out, with the result that the surface layers become brittle and fracture; this fracture travels progressively through the other wires.

Many other interesting features connected with the structure of wires can be detected with the aid of the microscope.

Piano or Music Wire.

This wire is usually made from a medium carbon steel in sizes varying from about 16 S.W.G. (0·064 inch) up to about 28 S.W.G. (0·0148 inch).

The following is a typical analysis of the steel used:

Carbon	0·60 per cent.
Silicon	0·09 ,,
Sulphur	0·02 ,,
Phosphorus	0·02 ,,
Manganese	0·43 ,,

The tensile strength of this wire varies from 100 to 160 tons per square inch for the above-mentioned sizes.

Plough Steel Wire.

Wire made from a crucible cast steel of high quality usually goes by the name of "plough steel" wire; this wire, which is made in all gauges from about 10 S.W.G. (0·128 inch) up to 28 S.W.G. (0·0148 inch) is used for aircraft bracing wires, for flexible and stranded wire cables, and similar purposes.

The following is a typical analysis of plough steel wire:

Carbon	0·85 per cent.
Manganese	0·60 ,,
Silicon	0·14 ,,
Sulphur	0·01 ,,
Phosphorus	nil
Copper	0·03 per cent.

The tensile strength of this wire varies from about 90 to 160 tons per square inch.

It is usually made in different qualities, or grades, according to the purpose for which it is required.

The following table shows a typical method of grading plough steel wire:

TABLE CII.

GRADES OF PLOUGH STEEL WIRE.

Grade.	*Tensile Strength, Tons per Square Inch.*	*Average Elongation per Cent.*
A	140 to 160	0·4
B	130 to 140	1·2
C	120 to 130	2·0
D	110 to 120	2·8
E	100 to 110	3·6
F	90 to 100	4·4
G	80 to 90	5·2

The grades most used in aircraft work are D and E. It is usual to galvanize or electro-plate with nickel these wires. Table CIII. gives the strength and weight of plough steel wires, as used in aeroplanes, and for rigid airship bracing work. The strengths are given for (*a*) a constant tensile strength of 100 tons per square inch, and (*b*) tensile strengths varying from 80 tons per square inch for 8 S.W.G. wire up to 140 tons per square inch for 30 S.W.G. wire; the latter values are approximately those obtained in wire drawing.

Fine Wires.

Wires of small diameter of carbon or alloy steel of from 0·040 down to 0·002 inch diameter are made by drawing through bort diamond dies, whilst copper wires are usually drawn through chilled cast iron dies in steps of about 1 S.W.G. at a time.

Alloy Steel Wires.

Alloy steels can be used for wire-drawing, but are not employed to any great extent, as the same results can usually be obtained with carbon steel wires.

Non-corrodible steel wire containing from 25 to 30 per cent. of nickel, and from 0·30 to 0·45 per cent. of carbon, is used for

TABLE CIII.

SIZES, WEIGHTS, AND STRENGTHS OF PLOUGH STEEL WIRE.

S.W.G.	Diameter.		Sectional Area Square Inch.	Weight in Pounds.		Breaking Load in Pounds.		
	Inches.	MM.		100 Yards.	1 Mile.	At 100 Tons per Square Inch.	At Tons per Square Inch.	Lbs.
7/0	0·500	12·7	0·1963	193·4	3404	43,975	—	—
6/0	0·464	11·8	0·1691	166·5	2930	37,854	—	—
5/0	0·432	11·0	0·1466	144·4	2541	32,820	—	—
4/0	0·400	10·2	0·1257	123·8	2179	28,144	—	—
3/0	0·372	9·4	0·1087	107·1	1885	24,350	—	—
2/0	0·348	8·8	0·0951	93·7	1649	21,300	—	—
0	0·324	8·2	0·0824	81·2	1429	18,464	—	—
1	0·300	7·6	0·0707	69·6	1225	15,830	—	—
2	0·276	7·0	0·0598	58·9	1037	13,400	—	—
3	0·252	6·4	0·0499	49·1	864	11,170	—	—
4	0·232	5·9	0·0423	41·6	732	9470	60	5680
5	0·212	5·4	0·0353	34·8	612	7900	65	5140
6	0·192	4·9	0·0290	28·5	502	6490	70	4550
7	0·176	4·5	0·0243	24·0	422	5450	75	4180
8	0·160	4·1	0·0201	19·8	348	4500	80	3600
9	0·144	3·7	0·0163	16·0	282	3650	85	3100
10	0·128	3·3	0·0129	12·7	223	2880	90	2590
12	0·104	2·6	0·0085	8·4	148	1900	95	1800
14	0·080	2·0	0·0050	5·0	88	1130	100	1130
16	0·064	1·6	0·0032	3·2	56	720	105	756
18	0·048	1·2	0·0018	1·8	32	406	110	446
20	0·036	0·9	0·0010	1·0	18	228	115	262
22	0·028	0·7	0·000615	0·610	10·7	138	120	166
24	0·022	0·56	0·000380	0·375	6·6	85·5	125	107
26	0·018	0·46	0·000250	0.250	4·4	57·0	130	74
28	0·0148	0·37	0·000172	0·168	3·0	38·6	135	52
30	0·0124	0·31	0·000121	0·119	2·1	27·2	140	38

hawsers, cables, and netting for sea-water use. The tensile strength of 12 S.W.G. (about $\frac{1}{10}$ inch) nickel-steel wire is about 90 tons per square inch, with an elongation of 6 per cent. in 2 inches, and an area contraction of 16 per cent.

International Aircraft Standard Specifications.

1. ROUND HIGH STRENGTH STEEL WIRE.

This specification covers solid high strength steel wire, round section, used in the consctruction of aircraft when flexibility is of minor importance.

WORKMANSHIP AND FINISH.—The wire shall be cylindrical and smooth and may show no evidence of scrapes, splints, cold shuts, rough tinning, or other defects not in accordance with best commercial practice.

Physical Properties and Tests—*Tensile Test.*—Samples for the tensile test shall be not less than 15 inches long and free from bends and kinks. In making tensile tests on aircraft wire, the distance between jaws of testing machine, with the sample in place and before test, shall be 10 inches. The wire must not break at less than the amount specified in the attached table, which is a part of this specification.

Torsion Test.—Samples for the torsion test shall be straight, and not less than 10 inches long. The sample shall be gripped by two vices 8 inches apart; one vice shall be turned uniformly at a speed not exceeding 60 revolutions per minute (on the larger sizes of wire this speed shall be reduced sufficiently to avoid undue heating of the wire). One vice shall have free axial movement in either direction. All wire shall be required to withstand the mini-

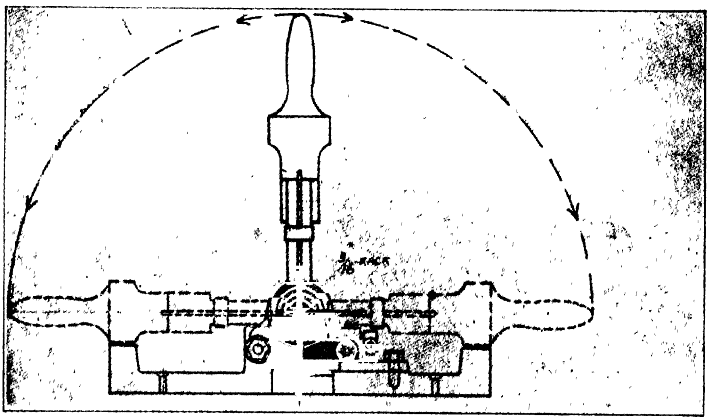


Fig. 186a.—Wire-Bending Test Apparatus.

mum number of complete turns shown in the attached table, and which are calculated from the relation Number of turns to be agreed upon between purchaser and manufacturer.

Bend Test.—Samples for bend test shall be straight and not less than 10 inches long. One end of the sample shall be clamped between jaws* having their upper edges rounded with 3/16 (0·188) inch radius. The free end of the wire shall be held loosely between guides and bent 90 degrees over one jaw; this is to be counted as one bend. On raising to a vertical position the count will be two bends. Wire shall then be bent to the other side, and so forth, alternating to fracture. The minimum number of bends required is stated in the attached table.

Wrapping Test.—A wrapping test is to be made on at least 10 per cent. of the total number of coils offered for inspection at one time. The wire is wrapped

* *Vide* Fig. 186a.

around its own diameter eight consecutive turns with a pitch substantially equal to the diameter of the wire and then unwrapped, maintaining the free end at approximately 90 degrees with the mandril. It must stand this test without fracture. Because of the possibility of personal error in making this test, failure on one test is not considered conclusive, and if required to do so the inspector shall make at least one, but no more than two, additional tests on the sample of wire. If any of these tests are successful, the material shall be passed as satisfactory in this respect.

Selection of Test Specimen.—A tensile, a torsion and a bend test shall be made on each end of each piece or coil of wire. When an individual coil of wire is to be divided into smaller coils to meet special requirements, it is sufficient to make one test on the original coil and to cut and seal the small coils in the presence of the inspector.

Dimensions and Tolerance.—All wire for this purpose shall be furnished in decimal sizes corresponding to the American Wire Gauge (Brown and Sharpe gauge).

A permissible variation of 0·002 inch above gauge on all sizes will be accepted, but no wire will be accepted having a variation of more than 0·0005 inch below gauge.

Table for Round High Strength Steel Wire.

American Wire Gauge.	*Diameter in Inches.*	*Weight in Pounds per 100 Feet.*	*Number of Bends through 90 Degrees.*	*Breaking Strength, Minimum Pounds.*	*Tensile Strength in Pounds per Square Inch.*
6	0·162	7·01	5	4,500	219,000
7	0·144	5·56	6	3,700	229,000
8	0·129	4·40	8	3,000	233,000
9	0·114	3·50	9	2,500	244,000
10	0·102	2·77	11	2,000	244,000
11	0·091	2·20	14	1,620	254,000
12	0·081	1·744	17	1,300	522,000
13	0·072	1·383	21	1,040	255,000
14	0·064	1·097	25	830	258,300
15	0·057	0·870	29	660	259,000
16	0·051	0·690	34	540	264,000
17	0·045	0·547	42	425	267,000
18	0·040	0·434	52	340	270,000
19	0·036	0·344	70	280	275,000
20	0·032	0·273	85	225	280,000
21	0·028	0·216	105	175	284,000

2. SPECIFICATIONS FOR HIGH STRENGTH STEEL WIRE.

General.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

Material.—2. The wire shall be manufactured of either I.A.S.B. standard steel No. 1065, No. 1070, or No. 1080, the compositions of which are listed below.

MANUFACTURE.—3. The steel used shall be manufactured by the acid open-hearth process. Every reasonable precaution shall be taken to keep different heats carefully separated and identified throughout the rolling and drawing of the wire and to the final stage of inspection and shipment.

It shall be uniformly coated with pure tin, to solder readily.

WORKMANSHIP AND FINISH.—4. The wire shall be cylindrical and smooth and may show no evidence of scrapes, splints, cold shuts, rough tinning, or other defects not in accordance with best commercial practice.

PHYSICAL PROPERTIES AND TESTS—*Tensile Test.*—5. (*a*) Samples for the tensile test shall not be less than 15 inches (381 mm.) long and free from bends and kinks. In making tensile tests on aircraft wire, the distance between jaws of testing machine, with the sample in place and before test, shall be 10 inches (254 mm.). The wire must not break at less than the amount specified in the attached table, which is a part of this specification.

Torsion Test.—(*b*) Samples for the torsion test shall be straight and not less than 10 inches (254 mm.) long. The sample shall be gripped by two vices 8 inches (203·2 mm.) apart; one vice shall be turned uniformly at a speed not exceeding 60 revolutions per minute (on the larger sizes of wire this speed shall be reduced sufficiently to avoid undue heating of the wire). One vice shall have free axial movement in either direction. All wire shall be required to withstand the minimum number of complete turns shown in the attached table, and which are calculated from the relation

$$\text{Number of turns} = \frac{2{\cdot}7}{\text{diameter in inches}} = \frac{68{\cdot}6}{\text{diameter in millimetres}}.$$

Bend Test.—(*c*) Samples for bend test shall be straight and not less than 10 inches (254 mm.) long. One end of the sample shall be clamped between jaws having their upper edges rounded with 3/16 (0·188) inch (4·76 mm.) radius. The free end of the wire shall be held loosely between two guides and bent 90 degrees over one jaw; this is to be counted as one bend. On raising to a vertical position the count will be two bends. Wire shall then be bent to the other side, and so forth, alternating to fracture. The minimum number of bends required is stated in the attached table.

Wrapping Test.—(*d*) A wrapping test is to be made on at least 10 per cent of the total number of coils offered for inspection at one time. The wire is wrapped around its own diameter eight consecutive turns with pitch substantially equal to the diameter of the wire and then unwrapped, maintaining the free end at approximately 90 degrees with the mandril. It must stand this test without fracture. Because of the possibility of personal error in making this test, failure on one test is not considered conclusive, and if required to do so the inspector shall make at least one, but no more than two, additional tests on the sample of wire. If any of these tests are successful, the material shall be passed as satisfactory in this respect.

SELECTION OF TEST SPECIMEN.—6. A tensile, a torsion, and a bend test shall be made on each end of each piece of coil or wire. When an individual coil of wire is to be divided into smaller coils to meet special requirements,

it is sufficient to make one test on the original coil and to cut and seal the small coils in the presence of the inspector.

DIMENSIONS AND TOLERANCES.—7. (*a*) All wire for this purpose shall be furnished in decimal sizes corresponding to the American Wire Gauge (Brown and Sharpe gauge).

(*b*) A permissible variation of 0·002 inch (0·051 mm.) above gauge on all sizes will be accepted, but no wire will be accepted having a variation of more than 0·0005 inch (0·013 mm.) below gauge.

DELIVERY, PACKING, AND SHIPPING.—8. (*a*) Wire covered by this specification shall be shipped in coils or bundles wrapped closely with a layer of plain strong paper in strips no less than 3 inches (76·2 mm.) wide and then covered with another wrapping of waterproof paper of an approved quality.

3. SPECIFICATIONS FOR CLEVELAND STEEL SERVICE OR LOCKING WIRE.

GENERAL.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

USE.—2. This wire shall be used for locking nuts and turnbuckles.

MATERIAL.—3. The wire shall be manufactured of either I.A.S.B. standard steel No. 1015 or No. 1020.

MANUFACTURE.—4. The wire shall be furnished in the soft-annealed condition, and shall be evenly and smoothly galvanized.

WORKMANSHIP AND FINISH.—5. The wire shall be cylindrical and smooth and must show no evidence of scrapes, splits, cold shuts, rough, or other defects.

PHYSICAL PROPERTIES AND TESTS.—6. The tensile strength must not exceed 75,000 pounds per square inch (52·7 kg. square mm.).

SELECTION OF TEST SPECIMENS.—7. When the wire is being unreeled to form small coils for shipment, specimens may be taken from the first, last, and any intermediate coil in the presence of an inspector who shall seal the small coils. Otherwise specimens shall be taken from 10 per cent. of the coils for each size.

DIMENSIONS AND TOLERANCES.—8. (*a*) All wire for this purpose shall be furnished in decimal sizes corresponding to the American Wire Gauge (Brown and Sharpe gauge).

(*b*) A permissible variation of 0·002 inch (0·051 mm.) above gauge on all sizes will be accepted, but no wire will be accepted having a variation of more than 0·0005 inch (0·013 mm.) below gauge.

DELIVERY, PACKING, AND SHIPPING.—9. (*a*) Wire covered by this specification shall be shipped in coils or bundles wrapped closely with a layer of plain strong paper in strips no less than 3 inches (76·2 mm.) wide and then covered with another wrapping of waterproof paper of an approved quality.

(*b*) The size and weight of packages or coils shall conform to the following unless otherwise specified on orders 0·072 inch (1·828 mm.) and larger, mean diameter of coils 22 inches (559 mm.), minimum weight of coil

25 pounds (11·34 kg.); 0·064 inch (1628 mm.) and smaller, mean diameter of coils 8 inches (305 mm.), minimum weight of coil 10 pounds (4·54 kg).

Inspection and Rejection.—10. A tag supplied by the manufacturer and filled in by the Government inspector with ink, showing the number of the test as per his official list of tests, the diameter of the wire, and the breaking strength, shall be attached to each coil or piece of wire accepted by him or by the salvage board. Such tag shall be sealed on the bundle with a steel wire of approved design and a lead seal bearing the private mark of the inspector doing the work.

Chemical Composition of Standard Carbon Steels.

No.	*Carbon.*	*Manganese.*	*Phosphorus (Max.).*	*Sulphur (Max.).*
1015	0·10 to 0·20	0·30 to 0·60	0·045	0·050
1020	0·15 to 0·25	0·30 to 0·60	0·045	0·050

Streamline Wires.

Modern aircraft invariably use bracing wires of streamline or elliptic section in all positions in which they are exposed to wind-resistance action.

It may be of interest to point out that a streamline section has only about $\frac{1}{6}$ of the wind resistance of that of a circular

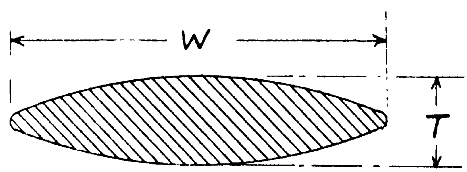


Fig. 187.

rod of diameter equal to the width or minor axis of the streamline section.

It is more convenient to manufacture the flat elliptical section sometimes termed "rafwire," shown in Fig. 187, than it is to make the ideal streamline shape, and if the fineness ratio is more than about 5 there is little difference in their resistances. Streamline wire is made from circular rods by cold swaging, during which process the material

becomes hardened; for aircraft work it is necessary to provide means for adjusting the tension, or length of these wires, and for this purpose the wires are made to approximately the correct lengths, and are left with a short distance at each end round, that is to say, the intermediate portion of the original rod is swaged down. The two ends of the wire are then screwed right- and left-handed, respectively, and adjustment is made by screwing the whole streamline wire around bodily, when it tightens or loosens itself in the end nuts provided on the anchoring clips. Lock nuts are provided to fix the wire in position.

A typical rafwire connexion is shown in Fig. 188; the swivelling trunnion shown, which forms the nut for the screwed end of the wire, is provided for the purpose of allowing self-alignment in the length of the wire, and to minimize the effects of lateral vibration.

The tensile strength of the screwed portion of the "butts," or circular ends, should be equal to that of the "blades," or flattened section; this effect is difficult to obtain, as the swaged portion hardens during manufacture, and as the screwing processes reduces the effective diameter.

Uniform strength in both blade and butt can be obtained by commencing with circular rods, initially butted at the ends; the percentage elongations of the material, however, will not necessarily be the same.

Swaging should not be carried too far, or the material will become brittle, and of low ductility.

The values given in Table CIV. were obtained from tests* made upon streamline wires:

The steel rod from which streamline wires are made should be true in diameter to within $\pm 0{\cdot}001$ inch, and should, before swaging or rolling, in its commercial state have a tensile strength of from 60 to 70 tons per square inch; this strength should not be diminished in the swaged condition. It is usual to specify that the original wire or rod shall be capable of being

* "The Use and Abuse of Steel," R. K. Bagnall-Wild, Proc. Inst. of Autom. Engrs., 1916-7.

TABLE CIV.

Results of Tests upon Streamline Wires.

Condition.	Blades.					Butts.			
	Width. Inches.	*Thickness. Inches.*	*Maximum Load in Tons.*	*Tensile Strength. Tons per Square Inch.*	*Elongation in 1 Inch per Cent.*	*Diameter in Inches.*	*Maximum Load in Tons.*	*Equivalent Maximum Load in Tons.*	*Tensile Strength. Tons per Square Inch.*
As manufactured ..	0·302	0·076	1·39	77·0	8	0·208	2·09	1·04	61·4
	0·292	0·077	1·39	78·5	7	0·207	2·14	1·07	63·5
	0·298	0·073	1·35	76·5	8	0·209	2·14	1·06	62·3
As manufactured ..	0·397	0·096	2·26	75·5	10	0·290	3·92	1·88	59·4
	0·405	0·099	2·42	76·8	9	0·293	4·03	1·89	59·7
	0·415	0·096	2·36	75·7	6	0·292	3·98	1·88	59·4
Annealed	0·301	0·075	1·19	67·2	14	0·207	2·05	1·03	60·7
	0·293	0·075	1·17	67·8	14	0·207	2·00	0·01	59·4
	0·297	0·073	1·12	65·8	10	0·208	2·02	1·02	59·4
Annealed	0·404	0·095	2·11	70·2	13	0·293	3·90	1·83	57·8
	0·408	0·096	2·06	66·9	12	0·293	3·97	1·86	58·9
	0·412	0·092	2·13	72·5	9	0·293	3·98	1·87	59·0

Note.—The "equivalent maximum load" is the estimated load on an area equal to the core diameter area of the screw thread.

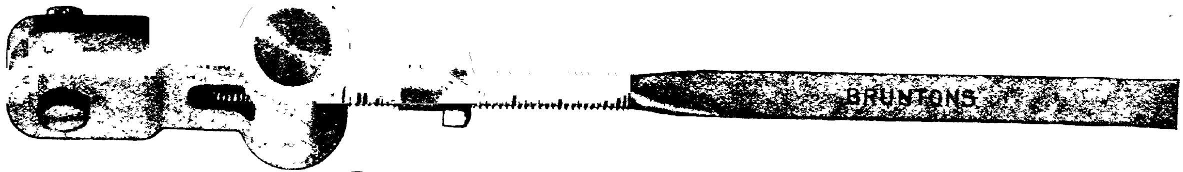


Fig. 188.—Rafwire Trunnion Joint for Bracing Wires.

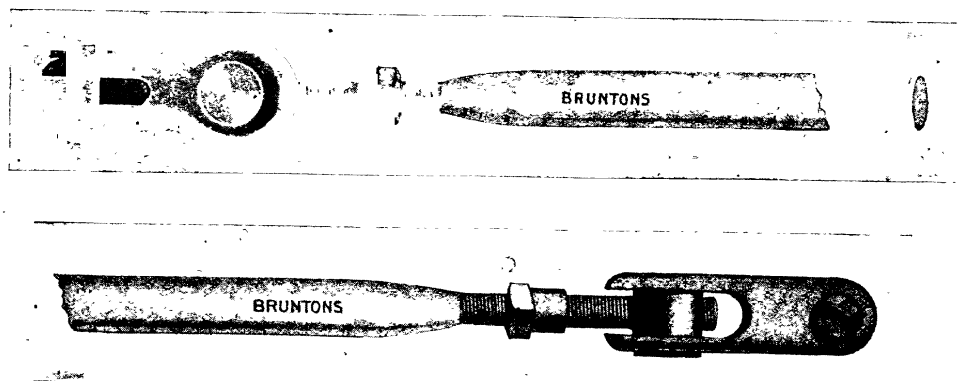


Fig. 188a.—Rafwire Trunnion Joints in Front and Side Elevations.

bent through 180° to an internal radius equal to the diameter of the rod, without cracks or flaws developing. After swaging, the swaged portion should have about the same tensile strength,

FIG. 189.—TYPES OF SWAGED RODS AND SECTIONS.

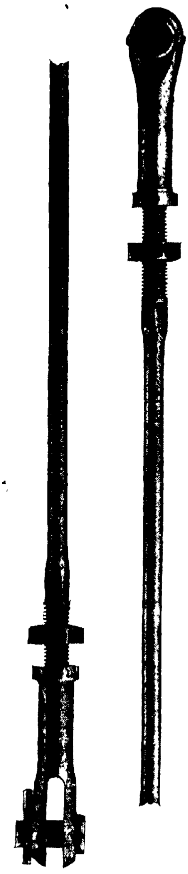


FIG. 190.—FUSELAGE BRACING WIRE.

and also should be capable of being bent cold through 180° to an inside radius equal to the smaller width or diameter of the section, without cracks or flaws developing.

Table CV. gives the size and strengths of Messrs. Bruntons' streamline wires for aircraft purposes, having the shape of section shown in Fig. 187.

TABLE CV.

SIZES AND STRENGTHS OF STREAMLINE WIRE. (Bruntons.)

Thread.	*Width.*	*Thickness.*	*Ultimate Strength in Lbs.*
Inches.	*Inches.*	*Inches.*	
4 B.A.	0·192	0·048	1050
2 B.A. . .	0·256	0·064	1900
$\frac{7}{32}$ B.S.F.	0·301	0·075	2600
$\frac{1}{4}$,, . . .	0·348	0·087	3450
$\frac{9}{32}$,, . . .	0·404	0·101	4650
$\frac{5}{16}$,, . .	0·440	0·110	5700
$\frac{11}{32}$,, . . .	0·496	0·124	7150
$\frac{3}{8}$,, .	0·540	0·135	8500
$\frac{13}{32}$,, . .	0·596	0·149	10,250
$\frac{7}{16}$,, .	0·636	0·159	11,800
$\frac{15}{32}$,,	0·692	0·173	13,800
$\frac{1}{2}$,, .	0·732	0·183	15,500
$\frac{9}{16}$,,	0·836	0·209	20,200
$\frac{5}{8}$,, .	0·924	0·231	24,700
$\frac{11}{16}$,, . . .	1·036	0·259	30,000
$\frac{3}{4}$,, .	1·116	0·279	35,000
$\frac{7}{8}$,, . .	1·316	0·329	48,000
1 ,, . .	1·516	0·379	65,000
$1\frac{1}{8}$,, . . .	1·708	0·427	80,000
$1\frac{1}{4}$,, . . .	1·928	0·482	103,000

Steel Cables.

In all cases in which a high tensile strength wire (combined with a certain degree of flexibility) is required, it is necessary to employ, not a single plough steel wire, but a cable or rope made up of a number of smaller wires of plough steel twisted together, so as to form a spiral circular rope.

The construction and sizes of steel cables vary considerably according to the purpose for which they are required, from the fine 19 wire single strand* Bowden cable of $\frac{1}{16}$-inch diameter, with a breaking load of about 6 cwt., up to the marine hawser cable, consisting of a 3-inch† outside diameter rope, composed of 6 strands each of 37 wires, with a breaking load of about 300 tons.

* *Vide* Fig. 191.

† Cables of 9-inch diameter and above are now made for marine salvage work.

TABLE CVI.

GENERAL PROPERTIES OF STEEL CABLES.

Type of Cable.	*Construction.*		*Girth of Cable. Inches.*	*Diameter of Cable (approx.). Inches.*	*Diameter of Wire. Inches.*	*Weight per 100 Feet. Pounds.*	*Breaking Load. Pounds.*
	No. of Strands.	*No. of Wires.*					
Instrument, control, and Bowden wire . . .	1	19	$\frac{1}{8}$	0·040	0·0080	0·35	285
Common Bowden wire	1	19	$\frac{13}{64}$	$\frac{1}{16}$	0·0125	0·90	675
Extra strong Bowden wire for motor-car brakes, etc.	1	19		$\frac{1}{8}$	0·0250	3·60	1350
Extra flexible aeroplane control cable (10 cwt.) .	7	19	—	0·115	—	2·0	1120
Flexible aeroplane bracing cable (25 cwt.) . .	1	19	—	0·143	—	4·3	2800
Flexible airship cable (60 cwt.)	7	37	—	0·418	—	28·9	6720
Mild plough steel crane cable (100 tons per square inch) flexible.	6	12	1	$\frac{5}{16}$	—	10·5	3920
Ditto. Special extra flexible	6	24	1	$\frac{5}{16}$	—	14·7	7280
Marine and mining cable (extra flexible) . .	6	37	5	$1\frac{9}{16}$	—	375	88 (tons)
Ditto	6	37	10	$3\frac{1}{8}$	—	1630	305 (tons)

Table CVI. on p. 451 illustrates the various types of steel cable in present-day use, and gives the properties of a typical example of each.

Strength of Cables.

The strength of a steel cable is invariably less than the net strength of the individual wires; the efficiency of a cable is expressed by the ratio of the actual to the net breaking strength of the total wires, and varies from 70 to 85 per cent.

The weight and strength increase approximately as the diameter of the cable, provided that the construction is the same; more exactly the weight and strength increase at a slightly higher rate.

Unwin* gives the following relations for the weights of wire ropes:

(*a*) For steel cables with hemp cores, weight per foot in pounds$=0\cdot15\gamma^2$, where γ=circumference of cable in inches.

(*b*) For all steel cables, weight per foot in pounds$=0\cdot17\gamma^2$.

TABLE CVII.

BREAKING STRENGTH OF CABLES. (Unwin.)

Girth $=\gamma$ inches.

Material.	*Breaking Strength in Tons.*
Charcoal iron wire	$1\cdot27\ \gamma^2$
Bessemer steel (mild) wire	$1\cdot7\ \gamma^2$
Crucible steel ,, ...	$2\cdot2$ to $3\cdot0\ \gamma^2$
Plough steel ,, ...	$3\cdot6$ to $4\cdot0\ \gamma^2$

Tables Nos. CVIII. and CIX. give the strengths of the larger round steel cables, as used for cranes, hoists, capstans, and general engineering haulage work.

Aircraft Cables.

There are two principal classes of steel cable employed in aircraft work—namely, (*a*) extra flexible cable for controls, and (*b*) Bracing cable.

* "Testing of Materials of Construction." W. C. Unwin.

TABLE CVIII.

Properties of "Mild Plough" Steel Wire Cable.
(Bullivant and Co., Ltd.)

Strength of wire = 100 tons per square inch.

Size Circumference.	*Diameter of Rope.*	*Flexible Steel Wire Rope, 6 Strands, each 12 Wires.*			*Extra Flexible Steel Wire Rope, 6 Strands, each 24 Wires.*		*Special Extra Flexible Steel Wire Rope, 6 Strands, each 37 Wires.*	
		Approximate Weight per Fathom.	Diameter of Barrel or sheave round which it may be at a Slow Speed worked	Guaranteed Breaking Strain.	Approximate Weight per Fathom	Guaranteed Breaking Strain	Approximate Weight per Fathom.	Guaranteed Breaking Strain.
Inches.	*Inches.*	*Pounds.*	*Inches.*	*Tons.*	*Pounds.*	*Tons.*	*Pounds.*	*Tons.*
1	$\frac{5}{16}$	0·63	6	1·75	0·88	3·25	—	—
$1\frac{1}{4}$	$\frac{13}{32}$	1·06	7·5	2·5	1·31	5	—	—
$1\frac{1}{2}$	$\frac{1}{2}$	1·44	9	4	1·88	7·5	2·0	8
$1\frac{3}{4}$	$\frac{9}{16}$	2·0	10·5	5·5	2·5	9·75	2·88	11
2	$\frac{5}{8}$	2·44	12	7	3·5	13	4·0	14·5
$2\frac{1}{4}$	$\frac{11}{16}$	3·37	13·5	9	4·5	16·25	4·88	17·5
$2\frac{1}{2}$	$\frac{13}{16}$	4·19	15	12	5·44	20·5	5·88	22
$2\frac{3}{4}$	$\frac{7}{8}$	5·25	16·5	15	6·25	24	7·0	26·5
3	$\frac{15}{16}$	6·25	18	18	7·63	28·5	8·25	32·25
$3\frac{1}{4}$	$1\frac{1}{16}$	7·06	19·5	22	9·37	34	10·38	37·5
$3\frac{1}{2}$	$1\frac{1}{8}$	8·25	21	26	10·75	39	11·5	43
$3\frac{3}{4}$	$1\frac{3}{16}$	9·87	22·5	29	12·19	45·5	13·38	50
4	$1\frac{1}{4}$	11·25	24	33	13·62	51·5	15·25	56·5
$4\frac{1}{4}$	$1\frac{3}{8}$	12·35	25·5	36	15·69	59	17·12	65
$4\frac{1}{2}$	$1\frac{7}{16}$	13·44	27	39	17·75	65	19·0	70·5
$4\frac{3}{4}$	$1\frac{1}{2}$	—	—	—	19·88	74	21·69	79
5	$1\frac{9}{16}$	—	—	—	22·5	82·5	24·38	88

The finer, or "bicycle," cable is also sometimes employed for working engine controls over a series of pulleys, or in the Bowden controls.

These cables can be obtained in the galvanized, tinned, or plated condition, and are preferable in one of these conditions for exposed situations.

Extra flexible cable for working aircraft controls, such as the elevators, ailerons, rudder, and adjustable empennage, are composed of a greater number of individual wires in the same sectional area than in the case of bracing or straining cables.

TABLE CIX.

PROPERTIES OF STEEL CABLES OF DIFFERENT STEELS. (Bullivant and Co., Ltd.)

Size Circumference.	*Diameter.*	*Approximate Weight per Fathom.*	"*Crucible*" *Steel.*	*Best Selected Improved "Crucible" Steel.*	*Best Selected "Mild Plough" Steel.*	*Best Selected "Extra Plough" Steel.*
Inches.	*Inches.*	*Pounds.*	*B.S. Tons.*	*B.S. Tons.*	*B.S. Tons.*	*B.S. Tons.*
$1\frac{1}{4}$	$\frac{13}{32}$	1·75	4·5	4·75	5·25	5·75
$1\frac{1}{2}$	$\frac{1}{2}$	2·5	6	6·5	7·25	7·75
$1\frac{3}{4}$	$\frac{9}{16}$	3·25	8·25	8·75	9·5	10·5
2	$\frac{5}{8}$	4	11	11·75	12·75	14·25
$2\frac{1}{4}$	$\frac{11}{16}$	5·25	14·25	15	16·5	18
$2\frac{1}{2}$	$\frac{13}{16}$	6·25	17·5	18·25	20	22·5
$2\frac{3}{4}$	$\frac{7}{8}$	7·5	21·25	22·5	24·75	27·25
3	$\frac{15}{16}$	9	24·75	26·5	29	31·75
$3\frac{1}{4}$	$1\frac{1}{16}$	10·5	29·75	31·75	35	38
$3\frac{1}{2}$	$1\frac{1}{8}$	13	34·5	36·75	40·25	44·25
$3\frac{3}{4}$	$1\frac{3}{16}$	14·5	39·5	42	46	50·75
4	$1\frac{1}{4}$	16·5	45·5	48·5	53	58
$4\frac{1}{4}$	$1\frac{3}{8}$	17·75	52·5	56	61·5	67
$4\frac{1}{2}$	$1\frac{7}{16}$	20	57·5	61	67	73
$4\frac{3}{4}$	$1\frac{1}{2}$	22	65	69	76	83
5	$1\frac{9}{16}$	25	72	76	83	92

The most commonly employed sections are those consisting of 7 strands of 7, 14, or 19 wires each, the diameters varying from 0·075 inch up to about 0·305 inch, with respective breaking strengths of 650 and 11,000 pounds.

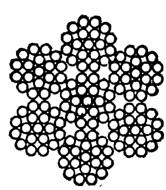


FIG. 191.—EXTRA FLEXIBLE CABLE SECTION (7 × 19).

Fig. 191 shows the construction of a typical 7 × 19 cable, and Tables CX. to CXII. gives the corresponding properties* in both English and Metrical Units.

* The author is indebted to Messrs. Brunton and Son, Musselburgh, Scotland, for the illustrations and particulars given.

TABLE CX.

Properties of Non-Flexible Cable (1 × 19).
(Messrs. Brunton and Son.)

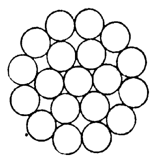


Fig. 191a.

METRIC MEASUREMENTS.

Diameter of Rope in Millimetres.	*Diameter of Wire in Rope in Millimetres.*	*Weight per 100 Metres in Kilos.*	*Breaking Strain of Rope in Kilos.*
1·0	0·20	0·53	130
1·1	0·22	0·64	160
1·2	0·24	0·76	180
1·3	0·26	0·89	205
1·4	0·28	1·03	235
1·5	0·30	1·18	265
1·6	0·32	1·35	305
1·7	0·34	1·52	345
1·8	0·36	1·70	385
1·9	0·38	1·90	430
2·0	0·40	2·10	475

ENGLISH MEASUREMENTS.

Circumference of Rope in Fractions of an Inch approximately.	*Diameter of Rope in Decimals of an Inch approximately.*	*Diameter of Wire in Decimals of an Inch.*	*Weight per 100 Feet in Pounds.*	*Breaking Strain of Rope in Pounds.*
$\frac{1}{8}$	0·040	0·0080	0·35	285
$\frac{9}{64}$	0·044	0·0086	0·43	350
$\frac{5}{32}$ bare	0·048	0·0094	0·51	410
$\frac{5}{32}$ full	0·052	0·0100	0·59	450
$\frac{11}{64}$	0·056	0·0110	0·69	520
$\frac{3}{16}$	0·060	0·0118	0·79	590
$\frac{13}{64}$	0·064	0·0125	0·90	675
$\frac{7}{32}$ bare	0·068	0·0133	1·01	760
$\frac{7}{32}$ full	0·072	0·0141	1·13	850
$\frac{1}{4}$ bare	0·076	0·0149	1·27	950
$\frac{1}{4}$ full	0·080	0·0160	1·40	1050

TABLE CXI.

PROPERTIES OF FLEXIBLE CABLE (7 × 7).
(Messrs. Brunton and Sons.)

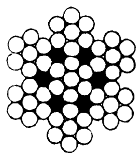


FIG. 191B.

METRIC MEASUREMENTS.

Diameter of Rope in Millimetres.	*Diameter of Wire in Rope in Millimetres.*	*Weight per 100 Metres in Kilos.*	*Breaking Strain of Rope in Kilos.*
1·8	0·20	1·25	290
2·0	0·22	1·52	350
2·3	0·25	1·95	430
2·5	0·27	2·28	480
2·75	0·30	2·82	595
3·0	0·33	3·40	720
3·3	0·36	4·05	855
3·5	0·38	4·55	950
3·7	0·40	5·00	1055
4·0	0·44	6·05	1275
4·3	0·47	6·90	1455
4·6	0·50	7·85	1650

ENGLISH MEASUREMENTS.

Circumference of Rope in Fractions of an Inch approximately.	*Diameter of Rope in Decimals of an Inch approximately.*	*Diameter of Wire in Decimals of an Inch.*	*Weight per 100 Feet in Pounds.*	*Breaking Strain of Rope in Pounds.*
$\frac{7}{32}$	0·070	0·007	0·83	640
$\frac{1}{4}$	0·080	0·008	1·01	770
$\frac{9}{32}$	0·090	0·010	1·30	950
$\frac{5}{16}$	0·100	0·011	1·52	1060
$\frac{11}{32}$	0·110	0·012	1·88	1310
$\frac{3}{8}$	0·120	0·013	2·27	1580
$\frac{13}{32}$	0·130	0·014	2·70	1880
$\frac{7}{16}$	0·140	0·015	3·03	2100
$\frac{15}{32}$	0·150	0·016	3·33	2320
$\frac{1}{2}$	0·160	0·018	4·03	2805
$\frac{17}{32}$	0·770	0·019	4·60	3200
$\frac{9}{16}$	0·180	0·020	5·23	3630

TABLE CXII.

PROPERTIES OF EXTRA-FLEXIBLE (AIRSHIP) CABLE (7 × 37).
(Messrs. Brunton and Son.)

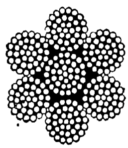


FIG. 191C.

METRIC MEASUREMENTS.

Diameter of Rope in Millimetres.	*Diameter of Wire in Rope in Millimetres.*	*Weight per 100 Metres in Kilos.*	*Breaking Strain of Rope in Kilos.*
6·0	0·31	12·9	2710
6·5	0·34	15·5	3270
7·0	0·36	17·4	3660
7·5	0·39	20·4	4300
8·0	0·42	23·7	4990
8·5	0·44	26·0	5470
9·0	0·47	29·7	6240
9·5	0·50	33·6	7070
10·0	0·52	36·3	7640

ENGLISH MEASUREMENTS.

Circumference of Rope in Fractions of an Inch approximately.	*Diameter of Rope in Decimals of an Inch approximately.*	*Diameter of Wire in Decimals of an Inch.*	*Weight per 100 Feet in Pounds.*	*Breaking Strain of Rope in Pounds.*
$\frac{3}{4}$	0·240	0·012	8·60	5960
$\frac{13}{16}$	0·260	0·014	10·33	7195
$\frac{7}{8}$	0·280	0·015	11·60	8050
$\frac{15}{16}$	0·300	0·016	13·60	9460
1	0·320	0·017	15·80	9980
$1\frac{1}{16}$	0·340	0·018	17·53	12,033
$1\frac{1}{8}$	0·360	0·019	19·80	13,720
$1\frac{3}{16}$	0·380	0·020	22·40	15,560
$1\frac{1}{4}$	0·400	0·021	24·20	16,810

Bracing Cable.

Cables are often employed for bracing aeroplane and airship structures, but have been replaced to some extent by streamlined section wires, or rafwires, in aeroplane work for exposed positions.

Where cables are exposed to wind action, the resistance is usually lessened considerably (from $\frac{1}{3}$ to $\frac{1}{5}$) by streamlining

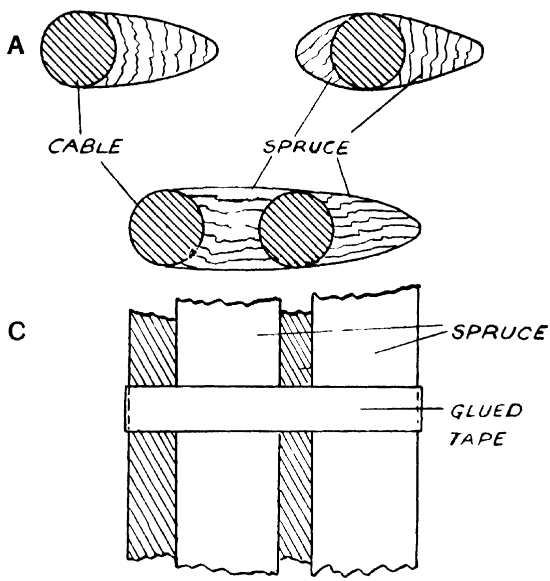


FIG. 192.—AERO. CABLE FAIRINGS.

the cables with wooden fairing in the shape of a tail portion; spruce is usually employed for this purpose, and the fairings are taped and glued to the cable at intervals.

Fig. 192 shows three typical methods employed for fairing exposed cables. Diagram A shows the ordinary tail piece fairing. Diagram B illustrates a fairing consisting of both a nose and tail piece, whilst diagram C shows the method adopted for fairing the duplicate left cables of an aeroplane wing.

Pulleys for Control Cables.

The pulleys should be grooved* to suit the cable radius of the ball-bearing type, and made in either brass, gun-metal, or aluminium alloy.

The diameter of the pulley should not be less than 20 times the diameter of the cable, or about 7 times the circumference; it is usual to provide guides near the pulleys, and wherever cables pass near a member of the machine, either bell-mouthed copper "fair-leads" or red fibre guides should be provided, These guides should be lubricated with thick grease.

International Aircraft Standard Cable Specifications.

The I.A.S.B. specify the following types of aircraft cables —namely, (*a*) Galvanized Single Strand, Non-Flexible with 19 wires; (*b*) Galvanized Multiple Cable, Flexible, 6 strands of 7 wires each; (*c*) Galvanized Multiple Cable, Flexible, 7 strands of 7 wires each; (*d*) Galvanized Multiple Cable, Extra-Flexible, 7 strands of 19 wires each.

The following table gives the properties specified for these cables:

TABLE CXIII.

I.A.S.B. Cable Specifications.

I.A.S.B. Designation.	*Diameter* *Inches.*	*Diameter* *Inches.*	*Breaking Strength in Pounds.*	*Approximate Weight per 100 Feet in Pounds.*
Single strand non-flexible (1×19) steel-wire cable	0·312	$\frac{5}{16}$	12,500	20·65
	0·250	$\frac{1}{4}$	8000	13·50
	0·218	$\frac{7}{32}$	6100	10·00
	0·187	$\frac{3}{16}$	4600	7·70
	0·156	$\frac{5}{32}$	3200	5·50
	0·125	$\frac{1}{8}$	2100	3·50
	0·109	$\frac{7}{64}$	1600	2·60
	0·094	$\frac{3}{32}$	1100	1·75
	0·078	$\frac{5}{64}$	780	1·21
	0·062	$\frac{1}{16}$	500	0·78
	0·031	$\frac{1}{32}$	185	0·30

* Either vee or semi-circular with sloping sides.

MANUFACTURE.—The steel wires composing the cable shall be laid around the centre wire in one or two layers as required by the number of wires in the cable with a left-hand (counter-clockwise) pitch and with a length of lay not to exceed 11 times the diameter of the cable or not less than 9 times the diameter of the cable.

Wires composing the cable shall be uniformly coated with pure tin or galvanized to solder readily.

I.A.S.B. Designation.	*Diameter.*		*Breaking Strength in Pounds.*	*Approximate Weight per 100 Feet in Pounds.*
	Inches.	*Inches.*		
Flexible 6×7 steel wire cable (cotton centre)	0·312	$\frac{5}{16}$	7900	15·00
	0·250	$\frac{1}{4}$	5000	9·50
	0·218	$\frac{7}{32}$	4000	7·43
	0·187	$\frac{3}{16}$	2750	5·30
	0·156	$\frac{5}{32}$	2200	4·20
	0·125	$\frac{1}{8}$	1150	2·20
	0·109	$\frac{7}{64}$	830	1·50
	0·094	$\frac{3}{32}$	780	1·30
	0·078	$\frac{5}{64}$	480	0·83
	0·062	$\frac{1}{16}$	400	0·73

MANUFACTURE.—The steel wires composing the individual strands of the cable shall be laid concentrically around the centre wire in one layer of six wires with a left-hand (counter-clockwise) pitch or lay. The cable itself shall be constructed by twisting six of these strands composed of seven wires each around a cotton centre with a right-hand (clockwise) pitch or lay of 6 to 8 times the diameter of the whole.

I.A.S.B. Designation.	*Diameter.*		*Breaking Strength in Pounds.*	*Approximate Weight per 100 Feet in Pounds.*
	Inches.	*Inches.*		
Flexible 7×7 steel wire cable (wire centre)	0·312	$\frac{5}{16}$	9200	16·70
	0·250	$\frac{1}{4}$	5800	10·50
	0·218	$\frac{7}{32}$	4600	8·30
	0·187	$\frac{3}{16}$	3200	5·80
	0·156	$\frac{5}{32}$	2600	4·67
	0·125	$\frac{1}{8}$	1350	2·45
	0·094	$\frac{3}{32}$	920	1·45
	0·078	$\frac{5}{64}$	550	0·93
	0·062	$\frac{1}{16}$	480	0·81

I.A.S.B. Designation.	*Diameter.*		*Breaking Strength in Pounds.*	*Approximate Weight per 100 Feet in Pounds.*
	Inches.	*Inches.*		
Extra-flexible 7 × 19 steel wire cable (for controls)	0·375	$\frac{3}{8}$	14,400	26·45
	0·344	$\frac{11}{32}$	12,500	22·53
	0·312	$\frac{5}{16}$	9800	17·71
	0·281	$\frac{9}{32}$	8000	14·56
	0·250	$\frac{1}{4}$	7000	12·00
	0·218	$\frac{7}{32}$	5600	9·50
	0·187	$\frac{3}{16}$	4200	6·47
	0·156	$\frac{5}{32}$	2800	4·44
	0·125	$\frac{1}{8}$	2000	2·88

MANUFACTURE.—The steel wires composing the individual strands of cable shall be laid concentrically around the centre wire in one layer of 6 wires and another, or outer, layer of 12 wires with a left-hand (counter-clockwise) pitch, the lay or pitch of both layers being of the same length; the cable itself shall be constructed by twisting 6 of these strands composed of 19 wires each around a seventh strand of the same construction and material with a right-hand (clockwise) pitch or lay of 6 to 8 times the diameter of the whole.

It is to be understood that the strand composing this cable must not necessarily be composed of wires all of the same diameter.

The following is a typical specification* of one of the I.A.S.B. aircraft cables:

3S14.—*Specification for 7×7 Flexible Steel Wire Cable.*

GENERAL.—1. (*a*) This specification covers the finish, material, and construction of high-strength steel wire cable composed of steel wires twisted concentrically around a steel wire centre, thus forming a strand, and such strands twisted concentrically around a central strand of the same construction, forming a cable.

(*b*) The general specification, 1G1, shall form, according to their applicability, a part of these specifications.

MATERIAL.—2. The wire shall be manufactured of either I.A.S.B. standard steel, No. 1065, No. 1070, or No. 1080, the compositions of which are listed below.

MANUFACTURE.—3. (*a*) The steel wires composing the individual strands of the cable shall be laid concentrically around the centre wire in one layer of six wires with a left-hand (counter-clockwise) pitch or lay. The cable itself shall be constructed by twisting six of these strands composed of seven wires each around a seventh strand of the same construction and material with a right-hand (clockwise) pitch and with a length of lay of six to eight times the diameter of the whole.

* The same general type of specification applies to all of the I.A.S.B. cables, the only differences lying in the constructions and strengths.

(b) The steel from which the wires composing the cable are drawn shall be manufactured by the acid open-hearth process.

(c) Wires composing the cable shall be uniformly coated with pure tin to solder readily.

(d) Joints in wires in cable having a diameter of 0·156 ($\frac{5}{32}$) inch (3·969 mm.) and larger shall be brazed in a gas fire. In cable having a diameter of 0·125 ($\frac{1}{8}$) inch (3·175 mm.) or less, wires may be joined either by brazing or twisting, at the manufacturer's convenience. Tucked-in or welded joints are not permitted. No two joints in individual wires shall be closer to one another in the completed cable than 30 feet (9·14 m.). All brazed joints shall be tinned. Exposed brass at joints shall not constitute cause for rejection.

Workmanship and Finish.—4. Each length of cable is to be evenly laid, and free from kinks, loose wires, or other irregularities. The cable shall remain in this condition when unwound from the reel or bend around a standard thimble, proper precautions being taken to secure the ends.

Physical Properties and Tests—*Tensile Test.*—5. (a) A tensile test shall be made upon each individual reel of cable purchased of a size.

(b) Samples of cable for testing for tensile strength shall be no less than 24 inches (610 mm.) in length. In making tests the distance between jaws of testing machine with sample in place and before test shall be not less than 10 inches (254 mm.).

(c) Samples for tensile test may be clamped in the jaws of the testing machine in the usual manner to facilitate testing; but in case of failure or dispute on individual tests and at the request of the manufacturer check tests shall be made by socketing the samples with pure zinc.

(d) Cable for use in the construction of aircraft shall meet the required breaking strength specified in the table.

Bend Test.—(e) One bend test is to be made on a sample cut from each reel of cable of a given size. Each sample must be bent once around its own diameter and straightened again at least 20 times in succession in the same direction of bending without any of the wires breaking.

Torsion Test.—(f) A torsion test is to be made on one wire from each sample of cable for tensile test. The wire is to be gripped by two vices 8 inches (203 mm.) apart. One vice shall be turned uniformly at as high a rate of speed as possible without perceptibly heating the wire. One vice shall have free axial movement in either direction.

(g) The number of complete turns which the wire shall stand is determined by the formula

$$\text{Number of turns} = \frac{2{\cdot}2}{\text{diameter in inches}} = \frac{55{\cdot}9}{\text{diameter in millimetres}}.$$

(h) Failure of one piece of wire to show full number of turns specified in the above torsion test shall not be considered cause for rejection, but in such case two additional tests shall be made on two more wires from the same sample of cable, and if both samples meet the requirements of the specifications the cable shall be accepted in this respect.

Dimensions and Tolerances.—6. There shall be no permissible variation in gauge below size. Cable having a diameter of $\frac{1}{16}$ to $\frac{3}{32}$ inch

(1·59 to 2·38 mm.), inclusive, shall have a permissible variation of 12 per cent. above size; cable having a diameter of $\frac{1}{8}$ to $\frac{3}{16}$ inch (3·18 to 4·76 mm.), inclusive, shall have a permissible variation of 10 per cent. above size; and cable having a diameter of $\frac{7}{32}$ to $\frac{3}{8}$ inch (5·56 to 9·53 mm.), inclusive, shall have a permissible variation of 7 per cent. above size.

DELIVERY, PACKING, AND SHIPPING.—7. (*a*) All cable shall be shipped on reels in lengths as specified on orders.

(*b*) The dimensions of reels for different lengths and sizes of cable shall conform to the table attached to this specification.

(*c*) A tinned or galvanized steel seal wire of approved design shall pass around no less than three convolutions of the cable on the reel and shall pass through a linen tag showing the name of the manufacturer, the size and length of cable on the reel, the order number or other distinguishing marks, and a record of the test for tensile strength. A lead seal impressed with the official stamp of the representative of the Government making the inspection shall secure the ends of this seal wire and furnish evidence of inspection and acceptance.

(*d*) The outer layer of cable on a reel ready for shipment shall be protected from mechanical injury in handling and transporting by an efficient covering of burlap.

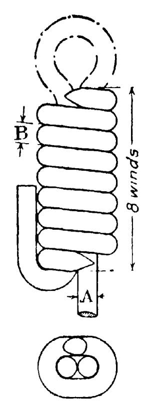


FIG. 193.—TYPICAL WIRE FERRULE JOINT.

Aircraft Wire Joints.

The common method of making an end joint with high tensile steel wire is to form a loop on the end, bring the end of the wire parallel and adjacent to the other straight portion, then slip a spring wire ferrule of the form shown in Fig. 193 over the two adjacent wires until it butts up against the loop; the free end of the wire is then bent up close to the ferrule.

It is usual to pass the wire through an eye-plate attachment before slipping the ferrule on, or to bolt the eye to a fork-end.

It has been known for some time that the ordinary wire ferrule joint, even when correctly made, has an efficiency of only about 60 to 70 per cent. of the wire strength, itself, and that failure generally occurs through the end of the wire pulling through the ferrule, or by fracturing on the loop.

A number of tests were made* by Messrs. J. A. Roebling and Co, upon the efficiencies of various forms of stay wire fastenings with the object of finding which was the best.

Fig. 194 illustrates some of the types of fastenings tested; the results of the tests are shown in Table CXIV.

The joint illustrated in Fig. 1 consists of a flattened copper tube, or strip, slipped over the bent wire, and soft soldered in position; this form is considered unsatisfactory for service, as the corrosive action of the soldering flux, and the heat, affect the strength of the wire. The type shown in Fig. 2 is that of the common ferrule joint above described. The radius of the curve at A and B should be exactly the same as at C, and no solder should be used. The ferrule should be of spring steel wire quality and should have from 7 to 10 turns, with an oval hole. In 80 per cent. of the tests upon this joint, the wire pulled through the joint, giving about 65 per cent. average efficiency, whilst in the case of the remaining 20 per cent., failure occurred by fracture at A, the average efficiency being 68 per cent.

Figs. 3, 4, and 5 show respectively different radii for the loop, pitch of spinal, and a method of wrapping the free end of the wire around the main stay wire in order to prevent slip. The efficiencies of these three joints are all low however.

Figs. 5 and 6 illustrate methods of binding the free end in order to prevent slip; the efficiency of this type of joint is about 70 per cent.

Figs. 7 to 10 denote methods of employing wedges to pre-

* National Advisory Committee for Aeronautics Report, 1915. Washington, U.S.A.

vent slipping of the free end; there is here an appreciable gain in efficiency, the average value being about 78 per cent.

Figs. 11, 12, and 13 show ferrule joints formed with double

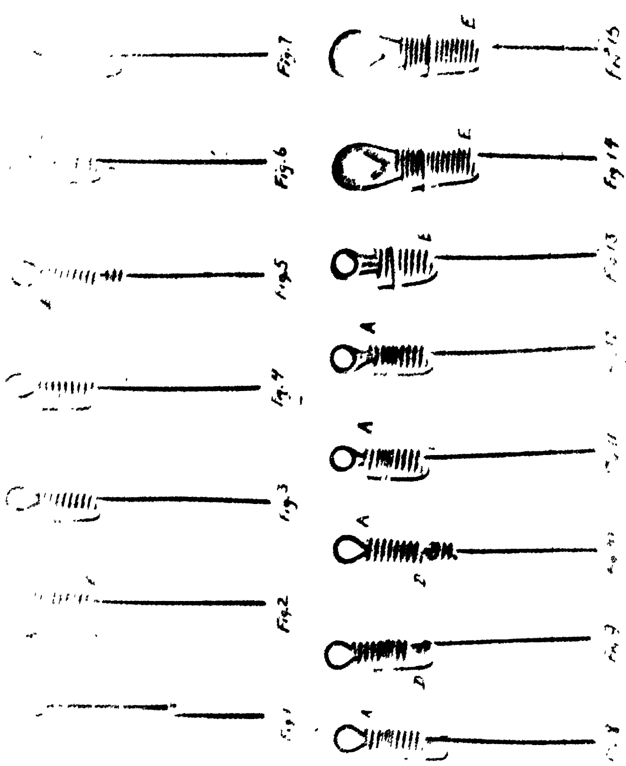


FIG. 194.—TYPES OF FERRULE JOINTS TESTED BY AMERICAN ADVISORY COMMITTEE FOR AERONAUTICS.

eyes without and with wedges; the average efficiency in these cases is about 83 per cent.

By employing a double eye with a tapered ferrule and one wedge between the ferrule and the eye, as shown in Fig. 13, a joint with an average efficiency of 85 per cent. is obtained.

The most efficient joints, however, are those illustrated in Figs. 14 and 15, in which a "thimble wedge"—that is, a thimble and wedge combined in one piece—is employed in conjunction with a tapered ferrule, and a wire-binding for the free end of the stay wire. The average efficiency of this joint is about 94 per cent.

The fracture in this case usually occurs in the thimble eye portion, as slipping of the stay wire is effectively prevented

TABLE CXIV.

SUMMARY OF RESULTS OF AIRCRAFT WIRE JOINT TESTS.

(For joints shown in Fig. 194.)

Terminal.	*Average Efficiency.*	*Range of Efficiency.*	*Points of Fracture.*	*Remarks.*
	Per Cent.	*Per Cent.*		
1	80	60 to 90	"A" or "B"	American soldered.
2	65	60 to 75	"A" or slipped	Foreign, proper eye.
3	62	60 to 65	Slipped ..	Foreign, improper eye.
4	60	59 to 61	do. ..	Right-hand ferrule.
5	72	65 to 75	"B" . .	End wrapped around stay.
6	70	68 to 78	"A" . .	End tied to ferrule.
7	82	80 to 84	"A"	Wedge under hook.
8	80	79 to 83	"A"	Two wedges with yoke.
9	70	60 to 75	"D"	Two wedges with washer.
10	84	75 to 87	"A"	Two wedges end wrapped.
11	80	74 to 82	"A"	Double eye, no wedge.
12	85	80 to 87	"A" .. .	Double eye, 1 wedge.
13	94	92 to 95	"E" .. .	Tapered ferrule, double eye, wedge.
14-15	94	92 to 96	"E"	Thimble wedge T. F. single eye.

Note.—These tests were made with wire having a diameter of 0·102 inch and a strength of 1600, 1800, and 2300 pounds. No difference in efficiency of stay was found by using wire of any of these strengths.

Steel Cable Splices and Connexions.

There are several ways of making connexions between cables and their attachments, the method adopted in each case depending upon the purpose for which the cable is used, and in many cases upon considerations of convenience.

The principal methods of making cable end connexions may be briefly classified as follows:

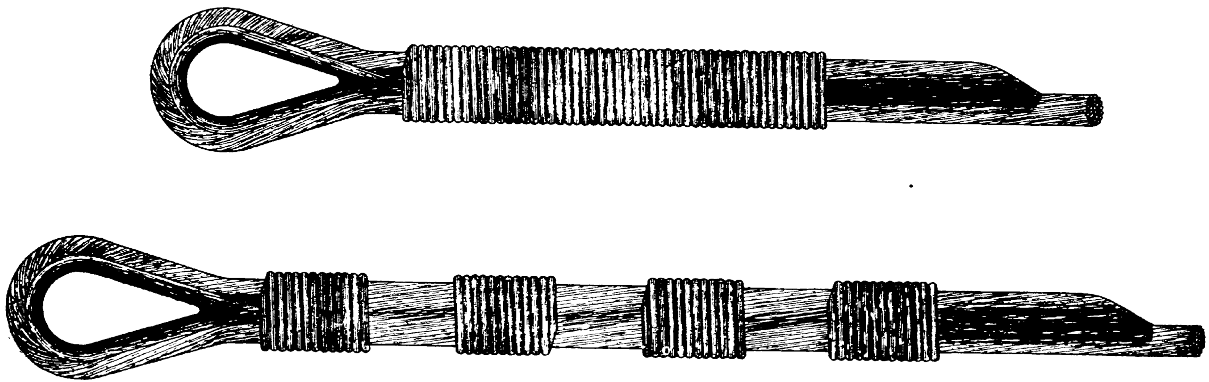


Fig. 195.—Standard Aircraft Cable Joints (Copper Wire Bound and Soldered All Along).
(The proportions shown in the diagrams are exactly to scale.)

1. By splicing, with or without thimbles.
2. By looping, binding with copper wire, or tubing and soldering.
3. By socket-soldering.

There are, of course, other methods of making connexions, but the above are those most commonly employed in aircraft work.

The method which was at one time the most widely adopted in aeroplane work, and which is still frequently employed, was the hand-splicing one, which required skilled workmanship, and which occupied an appreciable amount of time, but gave very good results as a rule.* With the introduction of quantity-production of aircraft, however, it was not possible to obtain a sufficient output of splices to keep pace with the other components, and it became the practice to adopt the second method mentioned above; this method when properly executed gives almost identical results with that of No. 1, but the joint suddenly changes in flexibility and section where the soldering ends, whereas the spliced joint gradually changes, and individual wires are less likely to fracture, when bent. An efficiency at the joint of almost 100 per cent. can be obtained with each one of the above methods.

Fig. 195 shows two standard aircraft cable joints of the soldered type (2), the proportions shown being accurately to scale.

Spliced Joints.

In marine and aircraft work, where splicing is possible, it is preferable, and if properly carried out will give a connexion as strong as the cable itself.

It is now the invariable practice to splice looped ends with a brass or galvanized iron thimble in the loop to protect the cable and to distribute the load over the loop.

There are two common methods of splicing employed for steel cable—namely, (*a*) the "Under and Over," or Crossed method, as shown in Figs. 197 to 202; and (*b*) the "Liverpool," "French," or Spiral method, as shown in Fig. 203.

The former is the method most commonly used in aircraft

* An average wire splicer could do a splice in a 5-millimetre cable complete in about 30 minutes.

work, and it has the advantage that the pull on the cable tightens the joint, and there is little possibility of the strands slipping. It shows a plaited appearance before serving.

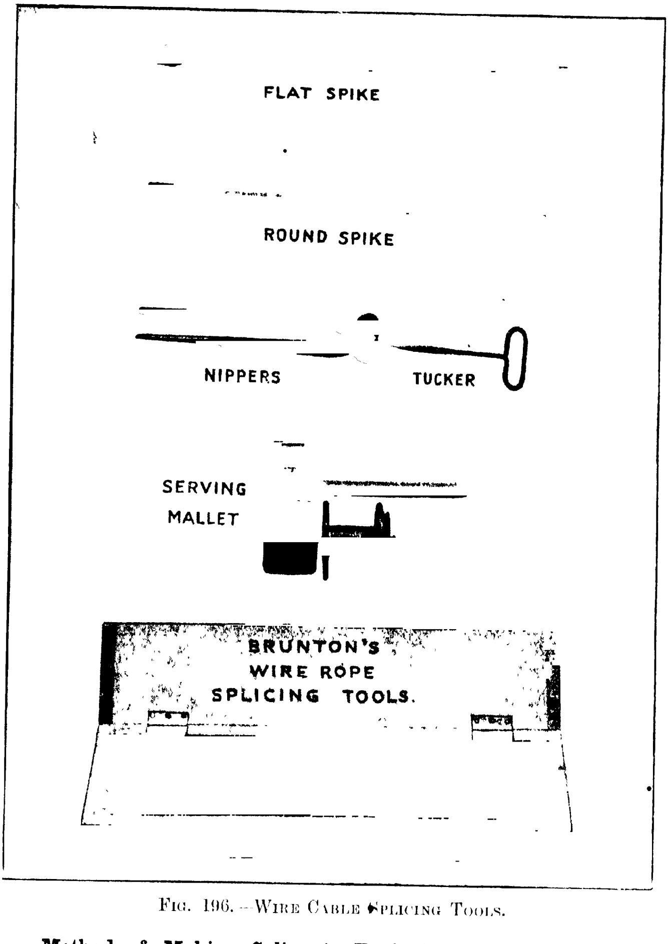


FIG. 196.—WIRE CABLE SPLICING TOOLS.

Method of Making Splices*—Tools Required.—The tools required for wire splicing comprise: (1) A flat marlin spike;

* The author is indebted to Messrs. Bruntons, of Musselburgh, Scotland, for the following description and illustrations.

(2) a round marlin spike; (3) a pair of wire-cutting nippers; (4) a "tucker," shaped similar to a wire gimlet, with pointed end (used for splicing small strands); and (5) a serving mallet, with bobbin for holding serving twine for finishing splices. These tools, the metal parts of which should be made of hand-forged best cast steel, are shown illustrated in Fig. 196.

The Under and Over Method—Instructions.—Serve the cable with wire tarred yarn (for large cables) or waxed thread (for small cables) to suit the circumference of the thimble, bend around the thimble, and tie securely in place with temporary

Fig. 197.

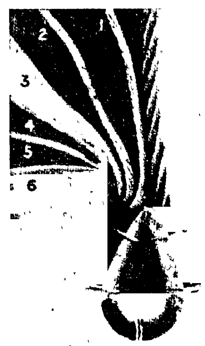


Fig. 198.

lashing until the splice is finished, as shown in Fig. 197. Open out the strands, as shown in Fig. 198, taking care to keep the loose end of the rope to the left hand (see Fig. 198). Now insert the marlin spike, lifting two strands (as shown in Fig. 199) and tuck away towards the right hand (that is, inserting the strand at the point, and over the spike) strand No. 1, pulling the strand well home. Next insert the marlin spike through the next strand to the left, only lifting one strand, the point of the spike coming out at the same place as before. Tuck away strand No. 2 as before.

The next tuck is the "locking tuck." Insert the marlin spike in the next strand, and missing No. 3, tuck away strand

No. 4 from the point of the spike towards the right hand. Now, without taking out the spike, tuck away strand No. 3, *behind the spike towards the left hand* (as shown in Fig. 200). Now

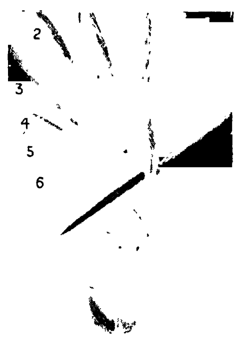


FIG. 199.

FIG. 200.

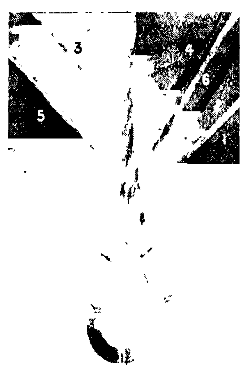


FIG. 201.

insert the spike in the next strand, and tuck away strand No. 5 behind and over the spike. Do No. 6 likewise. Pull all the loose strands well down.

This completes the first series of tucks, and the splice will,

if properly made, be as shown in Fig. 201. Next, starting with strand No. 1 and taking each strand in rotation, tuck away under one strand and over the next strand until all of the strands have been tucked *four times.*

If it is intended to taper the splice, the strands may at this point be split, and half of the wires being tucked away as before, the other half cut close to the splice. The finished splice is shown in Fig. 202 in the condition ready for serving.*

Serving is sometimes only applied to the tapered end of the splice in aircraft work, but for all ordinary purposes the whole splice may be served.

FIG. 202.—FINISHED SPLICE.

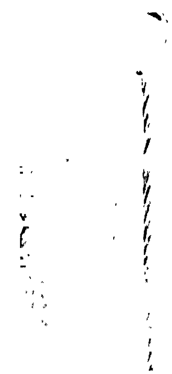


FIG. 203.—FRENCH OR SPIRAL SPLICE.

The Spiral, Liverpool, or French Splice.—The second method of splicing, which is shown illustrated in Fig. 203, has the appearance of a spiral cable similar to the unspliced cable, and is applicable to any cables or hawsers which do not hang free, nor are liable to spin or rotate. In this method the strands, instead of being interlocked together, are merely tucked round and round one particular strand in the rope. Each loose strand is, of course, tucked round a different strand in the cable.

* *Serving* is the name given to the method of binding the finished splice with waxed cord or twine, or tarred yarn, to protect the joint, and to prevent the loose wire ends from catching in objects.

Cable Sockets.

One method of making a strong end connexion, having at least the strength of the cable itself, is that shown in Fig. 78, and described in detail on p. 183.

Fig. 204 illustrates two types of Messrs. Bruntons' flexible cable sockets for soldered ends, one forming an ordinary eye, and the other a forked end.

The method recommended for making cable sockets is as follows: Put the socket over the cable, as shown in Fig. 205 (A), and about 6 inches from the end. Serve with fine wire for about 1½ inches, then open the strands, cut off the heart, and bend all of the strands back, as shown in Fig. 205 (B). These

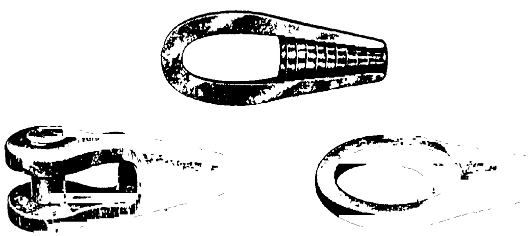


FIG. 204.—CABLE SOCKET FORK AND EYE.

strands should then be tucked in between the strands, as shown in Fig. 205 (C), and the whole hammered together. A steel pin should be driven in, as shown in Fig. 205 (C). The cable is then drawn into the socket, as shown in Fig. 205 (D), and the interior filled with a good hard white-metal.

The composition of a suitable white-metal is one consisting of equal parts of tin, lead, and zinc.

Another method of fastening cables to conical-ended sockets is as follows: A length of cable sufficient to allow of a testing length of usually six times the circumference, with a minimum of 15 inches between the grips, is cut off, the wires at each end are opened out, dipped in a strong solution of caustic soda or hydrochloric acid, washed and dried, and if necessary cleaned with emery paper. One of the prepared ends is then placed in a taper mould, the cable where it enters the mould being held

in clamps attached to the mould to ensure perfect centralization. The mould is then placed in a vice with the wider orifice uppermost and the opened-out wires at the top of the mould. Molten lead, to which 10 per cent. of antimony has been added, is then poured in and allowed to set. The same proce-

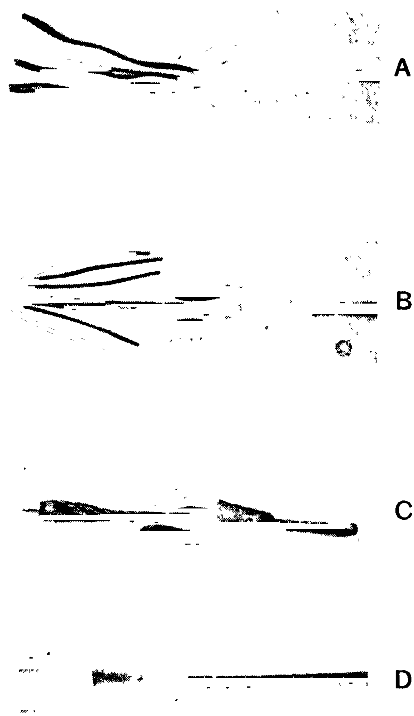


FIG. 205.—METHOD OF MAKING SOCKET JOINT FOR CABLE-END.

dure is then adopted with the other end. Before cutting off the test sample and opening out the wires it is necessary to whip or solder the cable in order to preserve the lay.

When the sample is cool, the cones may be attached in split ends; alternately the sockets themselves may form the moulds.

For multi-stranded cable, a good method (illustrated in

Figs. 206 to 209) is to bind the cable end at a distance equal to a little more than the socket-coned portion, and next, after separating and cleaning the strands with petrol to eliminate grease, to dip in a solution of equal parts of hydrochloric acid and water for a few minutes, and after cold-water washing to dry. The tops of the cable wires are then bound with a soft

Fig. 206.

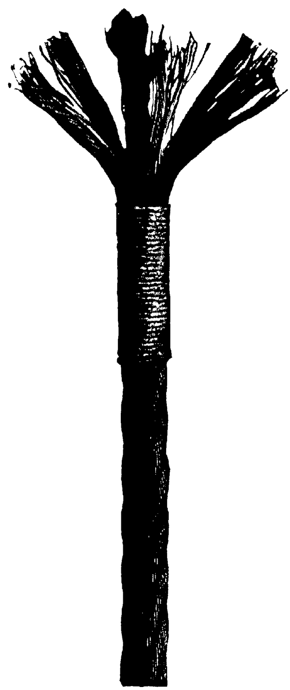


Fig. 207.

wire, pushed through the socket, until they are a little above the top, and the top soft wire binding pulled off, which allows the wires to spread out. Melted lead or low fusion point white metal is then poured into the socket, using clay around the bottom to prevent the molten metal from running out, and the joint is complete. The finished joint has the appearance indicated in Fig. 209.

Strength of Steel Cable Joints.

Except in the case of very small hand-spliced cables joints and extra flexible cable joints the efficiencies of spliced joints

FIG. 208.

FIG. 209.

vary from 90 to 100 per cent. The fracture of tested spliced cables usually occurs at the last tuck in the splice, and very seldom around the thimble. The efficiency of properly looped and soldered cable ends is almost invariably 100 per cent. The

TABLE CXV.

Breaking Loads and Efficiencies of Cable Joints.

Type of Joint.	*Cable.*	*Diameter, Inches.*	*Breaking Load of Cable, Pounds.*	*Breaking Load of Joint, Pounds.*	*Efficiency per Cent.*
Hand-spliced; over and under; thimble in each end.	Roeblings' single strand 19 wire (galvanized). Aviation type	$\frac{1}{16}$	500	500	100
		$\frac{1}{8}$	2100	2060	98·2
		$\frac{3}{16}$	4600	4180	91·0
		$\frac{1}{4}$	8000	7200	90·0
Hand-spliced, over and under; thimble in each end.	Roeblings. Seven strands of 19 wires each. Tinned. Aviation type	$\frac{1}{8}$	2000	1600	80·0
		$\frac{3}{16}$	4200	3500	83·5
		$\frac{1}{4}$	7000	6000	86·0
		$\frac{5}{16}$	9800	8200	83·5
		$\frac{3}{8}$	14,400	12,000	83·5
Looped and soldered joint. Length of lap = 20 times diameter of cable.	Roeblings' single strand of 19 wires (galvanized). Aviation type.	$\frac{1}{16}$	500	500	100
		$\frac{5}{64}$	780	780	100
		$\frac{3}{32}$	1100	1100	100
		$\frac{7}{64}$	1600	1600	100
		$\frac{1}{8}$	2100	2100	100
		$\frac{5}{32}$	3200	3200	100
		$\frac{3}{16}$	4600	4600	100
		$\frac{7}{32}$	6100	6100	100
		$\frac{1}{4}$	8000	8000	100

TABLE CXVI.

Tensile Strengths of Drawn Wires of Different Materials.

Material.	*Tensile Strength, Tons per Square Inch*	
	As Drawn.	*Annealed.*
Iron	30 to 40	20 to 30
Bessemer steel (mild)	40 to 50	25 to 35
Siemens-Martin steel (mild)	55 to 65	30 to 50
High carbon Siemens-Martin steel	50 to 80	—
Crucible cast steel (plough)	100 to 160	40 to 60
High nickel steel (28 per cent.) ($\frac{1}{10}$ inch diameter)	90	40 to 45
Copper	26 to 30	15 to 18
Phosphor bronze	45 to 75	23 to 30
Delta metal	45 to 65	35 to 40
Silicium bronze	28 to 50	—
Brass wire*	20 to 40	10 to 15
Aluminium wire	10 to 15	7 to 10

* The tensile strength increases with the percentage of zinc.

TABLE CXVII.

STRENGTHS OF WIRES OF VARIOUS MATERIALS. (Unwin.)
(Actual test results.)

Material and Condition.	*Diameter Tested, Inches.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. on 8 Inches.*	*Authority.*
Copper wire, annealed	0·32	14·7	39·8	Schüle and Brunner
Copper wire, annealed	0·14	15·0	38·4	,, ,,
Copper wire, annealed	0·16	15·7	35·9	,, ,,
Copper wire, annealed	0·08	16·1	35·7	,, ,,
Copper wire, annealed	0·04	15·9	33·8	,, ,,
Copper wire, half-hard	0·32	19·3	11·2	,, ,,
Copper wire, half-hard	0·24	20·0	7·1	,, ,,
Copper wire, half-hard	0·16	21·7	4·7	,, ,,
Copper wire, half-hard	0·08	23·9	1·7	,, ,,
Copper wire, half-hard	0·04	22·2	1·4	,, ,,
Copper wire, hard drawn	0·32	24·0	2·9	,, ,,
Copper wire, hard drawn	0·24	24·8	2·5	,, ,,
Copper wire, hard drawn	0·16	26·6	2·0	,, ,,
Copper wire, hard drawn	0·08	28·3	1·2	,, ,,
Copper wire, hard drawn	0·04	25·7	0·9	,, ,,
Brass wire	0·193	25·23	25·5	Unwin
Black cast steel rod ..	0·191	62·04	4·12	,,
Black cast steel rod ..	0·191	62·44	5·76	,,
Gilding metal (no tin)..	0·249	20·17	6·25	,,
Gilding metal (no tin)..	0·249	20·62	8·7	,,
Soft German silver ..	0·267	29·89	47·0	,,
Soft German silver ..	0·267	29·10	47·7	,,
Silicium bronze ..	0·080	27·5	1·5	Preece.
Silicium bronze ..	0·036	50·0	nil	,,
Delta metal (drawn) ..	0·115	58·2	2·1*	Fairfield Co.
Delta metal (annealed)	0·115	38·7	27·0*	,,

principal objections to this form of joint are the corrosive action within the strands of the flux, and the abrupt change from flexible to solid soldered joint, which weakens the joint when subject to bending action.

Table CXV. on p. 477 gives some typical test figures† for different cable end joints.

* In 6 inches.

† National Advisory Committee for Aeronautics, Report No. 3, 1915 Washington.

CHAPTER VIII

THE TREATMENT OF FERROUS MATERIALS

REFERENCE has already been made in the two previous chapters to the effects upon the properties of iron and steel of mechanical and thermal treatments, and a good idea of the results of forging, drawing, rolling, hammering, hardening, and tempering processes should have been already obtained

It is proposed in the present chapter to deal, in as brief a manner as possible, with the commercial processes, to which ferrous materials are subjected, in connexion with their applications to engineering purposes, as distinct from metallurgical processes, which are outside of the scope of a work of the present nature.

There are two distinct methods of treating steels* in commercial work—namely, the mechanical and the thermal, or heat treatment ones; these will be considered separately.

Mechanical Treatment.

This term includes the processes of hand and drop forging, cold and hot stamping, pressing, rolling, drawing, extruding, bending, and similar processes.

Forging.

The process of hand forging consists in shaping the material in the plastic or semi-molten state, by means of special tools such as hammers, sets, snaps, etc., by hand.

This process is employed for small quantity work, for repairs, and for very large forgings, such as those employed for large crank-shafts, connecting rods, guns, and the like; in the latter

* The term "steel" is here employed in the same sense as "iron."

cases, power hammers, either steam, pneumatic, electrical, or mechanical, are employed, but the actual shaping of the object is controlled by hand.

Hand forging necessitates considerable experience and skill on the part of the individual, and a thorough knowledge of the properties of the steel employed; for example, it is necessary to know the correct forging temperature, and the subsequent heat treatment for the particular steel employed.

Effect of Forging upon the Structure.

In the case of low carbon steels consisting of hard pearlite crystals with the soft ductile ferrite, or iron crystals, the effect

FIG. 210.—MICROGRAPH OF STEEL IN THE CAST CONDITION.

of forging, or doing mechanical work upon the material whilst hot, is to break up the crystals and to compress the cementing material; this effect is known as refining the structure, and may be clearly recognized from micrographs of steel before and after forging. The effect of forging may be roughly compared with that of hardening mild steel to a certain extent. Forging, at suitably high temperatures, is also favourable to crystal growth, but the temperature must not be allowed to fall below the recalescent point, at which temperature crystal growth ceases, otherwise the material becomes injured.

Figs. 210 and 211 show the effect of forging upon the structure of steel in the initially cast condition.

Drop Forging.*

This process consists in making the semi-molten, or hot and plastic material, flow under pressure or repeated hammer blows into the cavities formed in one or a pair of strong metal moulds, or dies. The process may be termed one of plastic deformation of steel.

The process, which yields results similar to those obtained by the casting method, possesses the advantages of yielding more homogeneous forgings, which may be made much stronger

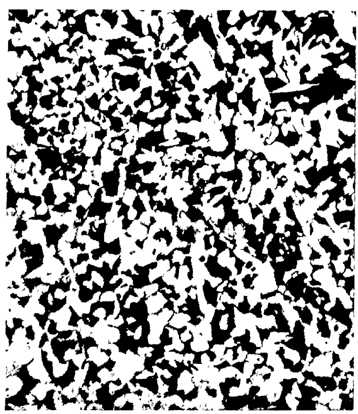


FIG. 211.—MICROGRAPH OF SAME STEEL AFTER FORGING

than any castings, and more accurate to shape, so that little, if any, machining is necessary, except for the faced or machined surfaces, holes, etc.

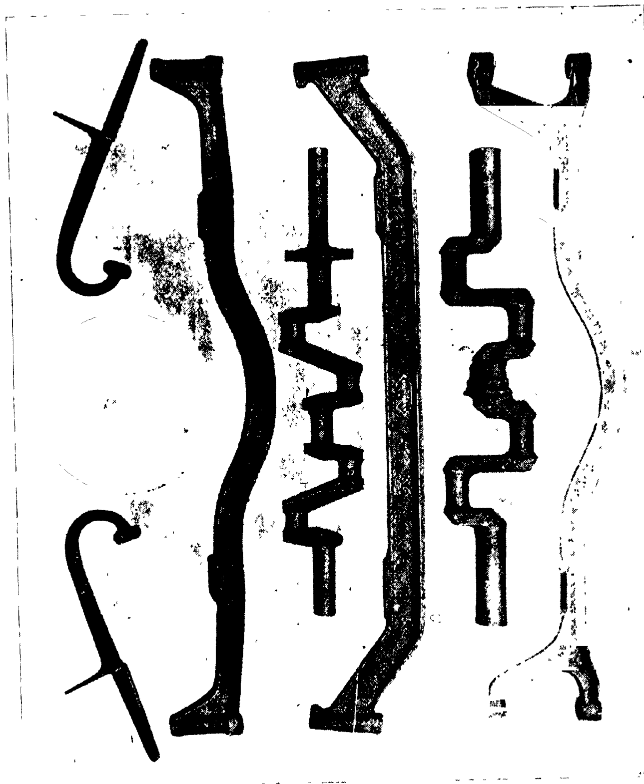
Moreover, the grain of the metal can be arranged to flow or run in the directions most advantageous from the point of view of strength;† for example, in the case of a gear-blank cut from

* An excellent paper entitled "Drop Forging and the Automobile Industry," by A. Stubbs, is given in the Proc. Inst. Aut. Engrs., May, 1915 Also *vide* "Shells and the Plastic Deformation of Steel," the Library Press, Ltd., 1919.

† See Figs. 150 to 153.

the solid bar, the teeth possess a fibrous structure parallel to the axis of the bar, whereas in the case of a drop forged blank, the fibre can be arranged so as to be radial.

Owing to the labour and expense incurred in making the necessary dies for drop forgings, the process does not pay,



except in the case of very simple objects, unless the quantities required are large; for example, in the case of certain automobile parts, in which great strength is not of primary importance, it is usually better to employ hand forgings or castings for quantities below from 50 to 100, as the cost of the dies would otherwise outweigh the other advantages.

Drop forgings can be produced in fairly complicated shapes, as shown in Figs. 212 and 213, from carbon steels containing a carbon content up to about 0·75, and from alloy steels* such as nickel, nickel-chrome, and chrome-vanadium steels; tensile strengths up to 120 tons per square inch, with a corresponding

FIG. 213.—OTHER TYPICAL DROP FORGINGS. (STUBBS.)

elastic limit of about 100 tons per square inch, can be obtained by suitable heat treatment of the two latter steels. In general, the softer the steel, the more easily can drop forgings be made from it.

* For the properties of such steels see Chapter VI.

It is possible to produce drop forgings to a tolerance of $\frac{1}{32}$ inch, in ordinary commercial work, and by careful forging and subsequent restriking in medium sizes, to obtain an accuracy within from 5 to 10 thousandths of an inch; for very accurate work multiple dies are employed, one set for roughing out, another for part-finishing, and a third for fine-finishing.

Materials for Drop Forging.

The principal steels employed for automobile and aircraft drop forgings are as follows—namely, (*a*) Mild-steels, from 0·10 to 0·25 per cent. carbon. (*b*) Medium carbon steels, from 0·30 to 0·50 per cent. carbon. (*c*) High carbon steels. from 0·5 to 0·8 per cent. carbon. (*d*) Nickel steels, low carbon, or case-hardening, and medium carbon nickel steels requiring subsequent heat treatment. (*e*) Nickel-chrome steels, with low chromium and nickel contents (analogous to low nickel steels) and with high chromium and nickel contents (air-hardening, high tensile steels). (*f*) Chrome-vanadium steels.

The mild steels employed should be made by the Siemens acid process and not by the basic process; they are employed for inexpensive lightly loaded parts and for case-hardened parts. These steels are very easy to drop forge, and give good impressions from the dies.

Medium carbon steels, made by the Siemens acid process, are employed for parts requiring "toughening," and which do not have to withstand heavy loads; these steels possess the properties of "40 ton" steel, and they can be readily machined.

It is possible to drop forge higher carbon steels (up to 1·0 per cent. carbon), but these steels are rarely employed in automobile work, and moreover are difficult to handle.

Nickel and nickel-chrome high tensile steels require special care in heating and forging, but yield exceedingly strong and light parts; unless, however, great care is taken, unsound forgings are liable to result, possessing surface defects such as "roakes"; these steels necessitate very strong dies, and even then the dies require more frequent replacement than when

used for the softer steels. There is no difficulty in drop forging the low carbon, low nickel steels, for case-hardening purposes, but the low carbon 5 per cent. nickel steel requires very careful handling for forging.

It is possible to drop forge some of the air-hardening nickel-chrome steels, but considerable care, combined with an experience of the suitability of these steels for particular parts, is

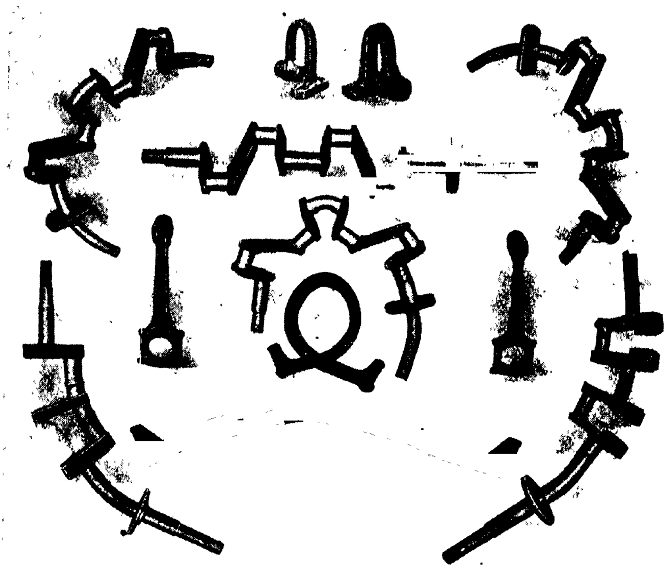


FIG. 214.—ILLUSTRATING TESTS TO DESTRUCTION OF DROP FORGINGS.

necessary; these steels are suitable for gear-blanks. Fig. 215* shows the results of cold bending tests upon nickel steel petrol engine connecting-rod drop forgings in the forged state, and Fig. 214 the results of destruction tests of stamped and forged automobile parts made by Messrs. Vickers, Ltd.

Chrome-vanadium steel possesses the advantages over nickel and nickel-chrome steels in that it is much easier to drop

* By courtesy of A. Stubbs and the Inst. of Autom. Engrs.

forge, but will give almost identical mechanical strength results, although its hardness properties are somewhat lower. These steels can also be much more readily machined.

Chrome-vanadium steels are particularly well suited to parts which require drop forging, and which must possess great shock resistance qualities, combined with high tensile strength. Many modern automobile parts are made from these steels.

Drop forgings from all steels must be carefully annealed after the stamping proccess, in order to relieve internal stresses, and to promote uniformity of structure

FIG. 215.—TESTS TO DESTRUCTION OF NICKEL STEEL DROP FORGINGS.

Dies for Drop Forgings.

The preparation of the dies requires special skill in order that the impressions obtained may be accurate; dies are sometimes cut by hand for small parts, but, wherever possible, dies should be machined in vertical millers, profiling, and similar machines, with the minimum of hand finishing work.

When the dies have been made, lead impressions are taken by running in molten lead, and the results are compared with the drawings; it is an advantage to prepare a wooden pattern of the finished object, to aid the die-sinker in making his dies.

TABLE CXVIII.

PROPERTIES OF DROP-FORGING STEELS. (Stubbs.)

Material.	*Condition.*	*Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Percentage Elongation in 2" Inches.*	*Reduction of Area per Cent.*
Mild steel (Siemens)	As forged	14 to 18	24 to 32	30 to 25	—
Medium carbon steel (Siemens) [0·30 to 0·50 C.]	Heat-treated (1)	25	40	20	40
Ditto	Heat-treated (2)	30	50	15	35
High carbon steel [0·50 to 0·80 C.]	As forged	30	54	10	25
Nickel Steels.					
3 per cent. nickel, 0·3 to 0·4 C.	Normal state	27 to 30	40 to 45	28 to 25	55 to 50
Ditto	Heat-treated	53 to 58	60 to 65	20 to 17	50 to 45
5 per cent. nickel, 0·3 to 0·4 C.	Normal state	33	50	22	45
Ditto	Heat-treated	70	80	12	35
Nickel-Chrome Steels.					
Nickel-chrome steel ..	Normal state	30 to 40	45 to 50	25 to 22	60 to 55
Ditto	Heat-treated (*a*)	48 to 77	55 to 85	23 to 14	60 to 50
Ditto	Heat-treated (*b*)	80 to 110	90 to 120	14 to 12	50 to 35
Chrome-Vanadium Steels.					
0·30 per cent. carbon; 1·2 per cent. chromium; 0·16 per cent. vanadium	Normal state	25 to 35	35 to 52	25 to 20	55 to 50
Ditto	Heat-treated	55 to 65	60 to 72	20 to 16	50 to 45
Air-hardening Nickel-Chrome Steels.					
0·35 per cent. carbon; 1·00 per cent. nickel; 0·50 per cent. chromium; 0·40 per cent. manganese	Annealed*	23	34	24	40
Ditto	Hardened†	50	58	17	45

Fig. 216‡ shows some typical forging and trimming dies together with a specimen finished.

The amount of taper, or draft, allowed varies from about 5 to 7 degrees, but will be greater for deeper forgings and for

* Brinell No. = 180 to 200. † Brinell No. = 210 to 290

‡ Courtesy of the Inst. of Autom. Engrs.

alloy steels. The amount of contraction allowed depends upon the shape and size of the forging and upon the forging heat; the average allowance is about $\frac{1}{64}$ inch per foot.

It is usual to allow from $\frac{3}{32}$ inch to $\frac{1}{4}$ inch for the "fin," or thickness of metal between the two dies, due to the flow of waste metal, but in the case of large and deep forgings the dies should be well guttered, in order to prevent choking and to facilitate the proper flow into all parts of the dies.

Small dies, when made in carbon or alloy steels, are carefully hardened before use, but in the case of large dies this treatment is often omitted owing to the risks of fracture.

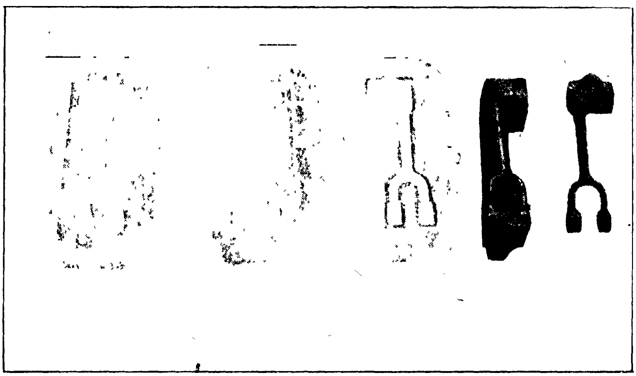


FIG. 216.—FORGING AND TRIMMING DIES. (A. STUBBS.)

It is essential during the forging process to keep the surfaces of the dies both cool and clear; this is usually accomplished by employing an air blast, and by employing a swab, or brush, in the forging intervals.

Oil is used to prevent the forged part from sticking in the die. The fins left on drop forgings, due to the die clearances, are cut off in a special trimming punch, using suitable dies.

The materials employed for the dies are cast iron (for fairly large and plain parts in iron or soft steel), Bessemer steel (for small quantity production of large and simple parts), high-grade Siemens acid steel (for tough dies for most general purposes), cast crucible steel (for small articles required in

large quantities, and for high carbon and alloy steel drop forgings). Occasionally nickel steels have been employed for very tough drop forgings.

The composition of one of the widely used Siemens acid steel for dies is as follows:

Carbon	0·65 per cent.
Manganese	0·60 ,,
Silicon	0·045 ,,
Sulphur	0·020 ,,
Phosphorus	0·025 ,,

It is not possible to dwell at any greater length upon the subject of drop forging, but for fuller information the reader is referred to the sources mentioned in the footnote on p. 481. Apart from the employment of drop forgings for motor-car parts, petrol engine parts, such as crank-shafts, connecting rods, valves, etc., these forgings are very suitable for quantity production of parts such as bolts, nuts, pins, eye-bolts, forked-ends, spanners, machine handles, tap-keys, hooks, lathe-carriers, and similar objects.

Stampings and Forgings in Other Materials.

It is also possible to stamp and forge other non-ferrous metals, such as the malleable bronzes, brasses, copper, Delta metal, and other metals, and for fairly simple parts, such stampings or forgings are almost equal to die-castings, and can be made much stronger. One firm has solved the problem of utilizing the "swarf" or waste material from the brass industry, and has produced stampings such as time fuses, butterfly nuts, unions, nipples, and a variety of other shapes therefrom.

Each particular material requires its own special conditions of heat treatment, temperature of forging, etc.; these conditions are referred to in the second volume of this work, dealing with the materials in question.

Normalizing Steel.

The processes of normalizing and annealing steel are to a certain extent similar in operation and in results, but in the former process, the temperature is usually higher than in the latter.

Normalizing consists in heating the steel to a temperature above the Ac_3 point and allowing it to cool slowly in still air; the process is employed not only for removing rolling, forging, and general mechanical treatment strains, but also to refine the structure and to present the material in the most suitable form for machining or hardening.

TABLE CXIX.

Effect of Annealing and Normalizing Carbon Steel Rolled Bars. (Harbord.)

Type of Steel and Condition.	*Period of Annealing, Hours.*	*Yield Point, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. in 2 Inches.*	*Reduction of Area per Cent.*
0·13 per cent. carbon					
As rolled	—	—	30·20	20·0	34·7
Annealed at 720° C. ..	½	11·34	20·16	44·5	73·26
Annealed at 800° C. ..	½	10·20	20·10	46·0	71·16
Normalized at 900° C. ..	½	13·00	21·50	45·0	71·16
Annealed at 720° C. ..	12	11·60	20·00	42·5	73·20
0·25 per cent. carbon					
As rolled	—	—	33·2	12·7	25·3
Annealed at 620° C. ..	½	27·80	34·5	24·0	55·0
Annealed at 720° C. ..	½	18·24	28·8	32·5	62·6
Annealed at 800° C. ..	½	19·40	29·4	29·5	58·6
Normalized at 900° C. ..	½	17·28	29·4	32·5	54·8
Normalized at 1100° C. ..	½	15·30	28·1	33·5	54·7
Annealed at 620° C. .	12	14·3	26·8	32·5	71·4
Annealed at 720° C. ..	12	15·8	28·2	31·0	57·3
Annealed at 900° C. ..	12	25·1	29·5	29·0	57·5
0·47 per cent carbon					
As rolled	—	—	37·0	6·25	18·76
Annealed at 620° C. ..	½	27·8	37·0	24·0	49·7
Annealed at 800° C. ..	½	18·7	33·0	27·5	45·6
Normalized at 900° C. ..	½	18·0	32·4	28·0	46·2
Normalized at 1100° C. ..	½	14·3	31·4	27·0	40·4
Annealed at 620° C. ..	12	21·1	32·0	33·0	57·6
Annealed at 900° C. ..	12	25·6	29·9	30·0	43·5
Annealed at 1200° C. ..	12	23·8	29·1	16·0	38·8
0·72 per cent. carbon :					
As rolled	—	—	49·0	11·72	3·43
Annealed at 620° C. ..	½	31·7	50·2	20·5	33·5
Annealed at 800° C. ..	½	—	42·5	17·7	31·7
Normalized at 900° C. ..	½	—	43·2	16·5	25·8
Normalized at 1100° C. ..	½	—	42·4	14·0	17·2
Annealed at 620° C. ..	12	21·1	40·6	29·5	46·5
Annealed at 900° C. ..	12	38·7	43·7	12·5	14·0
Annealed at 1200° C. ..	12	29·9	40·2	11·0	11·3

The following is the Engineering Standards Committee's definition of normalizing: "Normalizing means heating a steel (however previously treated) to a temperature exceeding its upper critical range and allowing it to cool freely in the air The temperature shall be maintained for about 15 minutes, and shall not exceed the upper limit of the critical range by more than 50° Centigrade."

The properties of steels in the normalized condition are given in Chapter VI., but Tables CXIX. and CXX. show the beneficial effect of normalizing rolled carbon and alloy steels.

TABLE CXX.

EFFECT OF NORMALIZING ROLLED ALLOY STEELS.

Material.	*Condition.*	*Elastic Limit, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent. in 2 Inches.*	*Reduction of Area per Cent.*	*Brinell Hardness.*
Low carbon 3 per cent. nickel steel (case-hardening)	As rolled	29·5	35·3	38·5	53·0	169
	Normalized	21·3	32·5	33·0	60·0	—
Medium carbon 3 per cent. nickel steel	As rolled	29·5	41·9	36·5	50·1	217
	Normalized	22·6	36·8	29·0	51·0	—
Medium carbon 5 per cent. nickel steel	As rolled	37·5	45·1	32·5	44·6	202
	Normalized	30·5	45·1	24·0	29·2	—
High nickel-chrome steel	As rolled	56·9	75·1	6·0	8·7	—
	Normalized	67·2	83·0	14·0	36·0	364
3 per cent. nickel-chrome, medium carbon content steel	As rolled	60·1	76·9	9·0	18·4	—
	Normalized	67·8	78·8	13·0	35·9	340
Higher carbon nickel-chrome steel	As rolled	57·0	75·1	8·0	16·2	—
	Normalized	77·5	85·4	5·5	14·8	364

Annealing.

The process of annealing is usually understood to mean the reheating of a steel after mechanical treatment to a temperature depending upon the nature of the steel, but usually just below the critical point, followed by a slow cooling in free air or a badly conducting medium. Annealing usually occupies a

* Messrs. Sandersons and Newbould's steels.

much longer period of time than normalizing, and in many cases is a more elaborate process.

The following is the Engineering Standards Committee's definition of the term "annealing": "Annealing means reheating followed by slow cooling. Its purposes may be:

"(*a*) To remove internal stresses or to induce softness, in which case the maximum temperature may be arbitrarily chosen. (*b*) To refine the crystalline structure in addition to the above (*a*), in which case the temperature must exceed the upper critical range as in normalizing."

All metal parts which have been subjected to forging, stamping, rolling, and similar mechanical treatment should be annealed; micrographs of similar steels before and after such annealing reveal the beneficial effects as shown by the more uniform and finer grain or crystalline structure.

Figs. 135 and 145 show the effect of annealing in the case of air-hardening nickel-chrome steel, whilst Figs. 166 and 167 show the beneficial effect upon the structure of annealing steel castings.

The material in the annealed* state is in its most ductile and workable condition, and its tensile strength and hardness are at their minimum values; the material should therefore be machined in the annealed state.

Annealing Processes.

The objects to be annealed should be slowly heated up in a closed-in furnace or muffle, free from draughts, until the correct annealing temperature is attained (which is usually just below the critical point), when the temperature should be kept uniform for several hours, the exact time depending upon the size and material of the object.

Small low carbon steel objects when annealed in a box take from one to three hours; large alloy steel articles from three to eight hours.

At the termination of the annealing period, the objects should be allowed to cool down very slowly either by (*a*) shutting

* For test results upon annealed materials see Chapters V. and VI.

off the furnace heat supply, and allowing the whole to cool naturally; or (*b*) burying the objects taken from the furnace in fine ashes, dry sand, sawdust, or lime, and allowing them to cool.

Method (*a*) is the better, when it can be conveniently employed, as it excludes the possibility of too rapid initial cooling and of uneven cooling due to draughts when withdrawing from the furnace to the cooling medium as in case (*b*).

It is of great importance not to heat the steel to too high a temperature, or too rapidly, otherwise the grain will be found to be coarse.

The period required for annealing steel castings* usually varies from 16 to 32 hours, and for malleable iron from 60 to 120 hours, the temperature of annealing being 900° to 950° C. for the Reamur process, and 800° to 850° C. for the black-heart type of malleable iron.

Box Annealing.

The better method of annealing small and medium steel objects is known as the " box annealing " method, in which the parts are placed in a steel plate, or cast-iron box, lined with firebrick, and the whole gradually heated to the annealing temperature, and after the stipulated period allowed to slowly cool.

In all cases of annealing steel objects, care should be taken to prevent the access of air to the heated parts, otherwise surface oxidation or decarbonization will occur. In box annealing, the edges and openings of the box should be filled up with fireclay, and in many cases it has been found advantageous to fill the empty space in the annealing box with sand, fireclay, slaked lime, fine ashes, or charcoal; alternatively a little resin placed in the box is effective, and the other materials mentioned need not be used.

When using cast-iron boxes it is essential to prevent the steel objects from coming into direct contact with the sides of the box, as cast iron has a great affinity for carbon, and will

* For fuller particulars, see p. 336 *et seq*

therefore tend to decarbonize the steel; where such boxes are used, a layer of charcoal or lime, or a lining of firebricks, must be used.

A quick annealing process consists in heating the steel to a red heat (750° to 800° C.) an hour or so, then placing it in dry sand, lime, sawdust, or fine ashes, well covering it, and allowing it to cool slowly.

Many objects can be conveniently annealed by heating them in a lead bath,* and allowing them to cool in sawdust.

Handling of Heated Objects.

When heated objects are removed from the hardening or annealing ovens, they should be gripped with *heated tongs*, otherwise local cracks and hardness variations are apt to occur; the tongs, or grips, should be heated at least to a black heat (350° to 400° C.).

TABLE CXXI.

ANNEALING TEMPERATURES FOR TOOL STEELS.

Type of Steel.	*Temperature of Annealing.*		*Period.*	*Remarks.*
	° *Cent.*	° *Fah.*	*Hours.*	
No. 1 temper, $1\frac{1}{2}$ per cent. carbon	720	1328	1 to 4	These temperatures should not be exceeded, and tools should be box annealed.
No. 2 temper, $1\frac{1}{4}$ per cent. carbon	720	1328	1 to 4	
No. 3 temper, $1\frac{1}{8}$ per cent. carbon	720	1328	1 to 4	
No. 4 temper, 1 per cent. carbon	720	1328	1 to 4	
No. 5 temper, $\frac{7}{8}$ per cent. carbon	750	1382	1 to 4	
No. 6 temper, $\frac{3}{4}$ per cent. carbon	770	1418	1 to 4	
High-Speed Tool Steel.				
Tungsten 8 to 18 per cent. Chromium 4 to $5\frac{1}{2}$ per cent.	870	1600 to 1700	2 to 3	Heat slowly so that tools take from 1 to 2 hours to attain annealing temperature, then keep at same for 2 to 3 hours, and allow to cool in furnace, or bury in sawdust, lime, dry sand, etc.
Carbon 1·8 to 0·7 per cent. Vanadium 0 to 0·29 per cent.	928	1600 to 1700	2 to 3	

* The same precautions must be taken as those mentioned on p. 510.

Annealing Tool Steels.

Table CXXI. shows the temperatures recommended for the annealing temperatures of typical carbon and high-speed tool steels.

Annealing of Cast Iron.

The results shown graphically in Fig. 217 illustrate the effect of annealing cast iron, such as that used for petrol engine

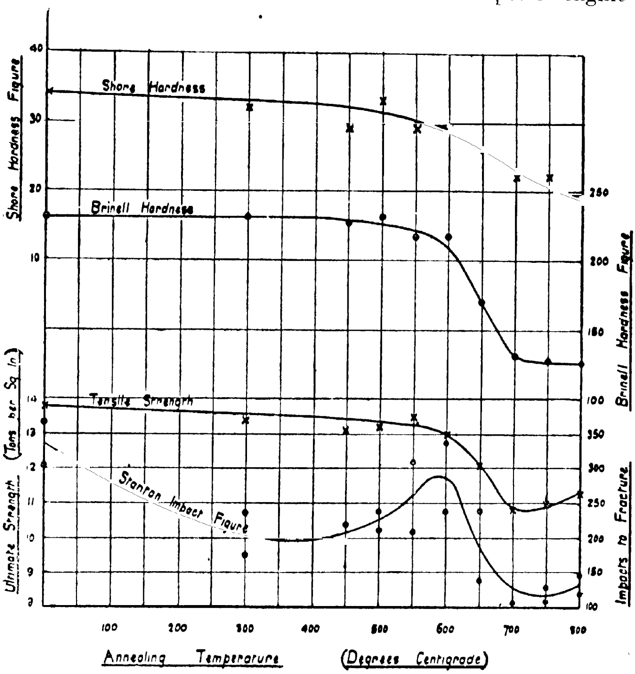


FIG. 217.—ANNEALING TEMPERATURES AND MECHANICAL PROPERTIES OF CAST IRON FOR AUTOMOBILE WORK.

pistons, at different temperatures.* Apart from the beneficial effects of annealing, in removing casting stresses, and in improving the structure, it will be seen that up to about 500° C. there is practically the same tensile strength and hardness, but that

* R. T. Rolfe, *Aeron. Journ.*, 1917.

the impact value is markedly affected. Annealing from above about 600° C. the strength and hardness are seriously diminished.

Local Annealing of Hardened Parts.

Hardened steel parts, such as case-hardened articles, Harveyized* nickel or carbon steel plate, etc., may be softened locally by heating the place with an electric arc, or oxy-hydrogen flame.

Armour plates with chilled surfaces are softened in this way for drilling purposes.

The subject of local annealing is somewhat allied to that of local hardening; methods of local hardening case-hardening steels are considered at the end of this chapter.

The Hardening of Steels.

The effects upon the mechanical properties of carbon and alloy steels of specified hardening processes have been considered in some detail in Chapters V. and VI., whilst the effects of hardening upon the micro-structure, and the constituents of steels, has been referred to in Chapter IV.

By hardening is meant the process of heating a steel above its critical point and allowing it to cool at a given more or less rapid rate; in general, the quicker the cooling the harder and more brittle will the material become, and the slower the cooling the softer and more ductile will it become.

The following is the Engineering Standards Committee's definition of hardening: Hardening means heating a steel to its normalizing temperature and cooling more or less rapidly in a suitable medium—*e.g.*, water, oil, and air.

Theory of Hardening.

The effects of quenching or rapid cooling of carbon and alloy steels have been alluded to in Chapter IV., and the results may

* The process of Harveyizing steel plate consists in covering it with carbonaceous material and heating to 850° to 950° for about 120 hours, followed by water jet quenching.

be briefly summarized in stating that the effect of quenching or rapidly cooling steel from a temperature above the critical points (Ar_3, Ar_2, and Ar_1) is to arrest the transitional products or to retain the solid solution state,* so that in the case of medium and high carbon steels instead of allowing ferrite and pearlite to remain, other constituents such as martensite, austenite, troosite, etc., are obtained. When steel exists in the quenched state, the presence of these constituents increases the tensile, compressive, shear and yield strengths, and also the hardness, but in general tends to reduce the elongation or decrease the ductility.

In the case of carbon steel containing from 0·3 to 0·4 per cent. of carbon, it is necessary, not only to raise the temperature to the point at which the solid solution areas are formed, but also to ensure that the temperature is high enough to cause the ferrite to disappear, or to dissolve in the solid solution. Figs. 135, 145, 164, 165, 176, and 177 show the effects of hardening upon the structure of steel.

The correct temperature for hardening, or rather quenching, then, is that at which there is a homogeneous solid solution; this temperature is about 800° to 850° C. for the steels mentioned, but the true temperature for any steel depends upon the critical or change points. Particulars of hardening temperatures for special steels are usually supplied by the manufacturers.

The effect upon the constitutions of carbon steels ranging from 0·09 up to 2·5 per cent. carbon content, of quenching from, or above the Ar_3, Ar_2, and Ar_1 points, is shown in Table CXXII. In all cases the quenching was drastic, that is to say, the cooling was very rapid.

In the case of mild steel (0·09 carbon), the effect of lowering the quenching temperature from above Ar_3 to below Ar_1 is to progressively reduce the amount of martensite, and to increase the ferrite content.

With high carbon steels there is no ferrite present at all.

* See Fig. 144.

TABLE CXXII.

Constituents of Quenched Carbon Steels. (Harbord.)

Percentage of Carbon.	*Quenched above Ar_3.*			*Quenched between Ar_3 and Ar_2.*			*Quenched between Ar_2 and Ar_1.*			*Quenched below Ar_1 or Cooled Slowly.*		
	Martensite.	*Cementite.*	*Ferrite.*	*Martensite.*	*Cementite.*	*Ferrite.*	*Martensite.*	*Cementite.*	*Ferrite.*	*Martensite.*	*Cementite.*	*Ferrite.*
0·09	0·73	—	0·23	0·27	—	0·73	0·11	—	0·89	0·10	—	0·90
	Quenched above Ar_2.											
	Martensite.	*Cementite.*	*Ferrite.*									
0·21	1·00	—	—				0·31	—	0·69	0·23	—	0·77
0·35	1·00	—	—				0·56	—	0·44	0·50	—	0·50
	Quenched above Ar_1.											
	Martensite.	*Cementite.*	*Ferrite.*									
0·80	1·00	—	—							1·00	—	—
1·20	0·94	0·06	—							0·92	0·80	—
2·50	0·80	0·20	—							0·77	0·23	—

Note.—The constituents are expressed in terms of volumes, the total volume in each case being unity.

Effect of Initial Temperature and Rate of Cooling.

For any given carbon or alloy steel the degree of hardness will depend firstly upon the initial temperature at which cooling begins, and secondly upon the actual rate of cooling; the effect of the size or mass of the object also has an effect, but this will be considered later.

The subject of cooling rates was briefly dealt with in Chapter IV. and it was shown there that the more rapid the cooling the harder became the material.

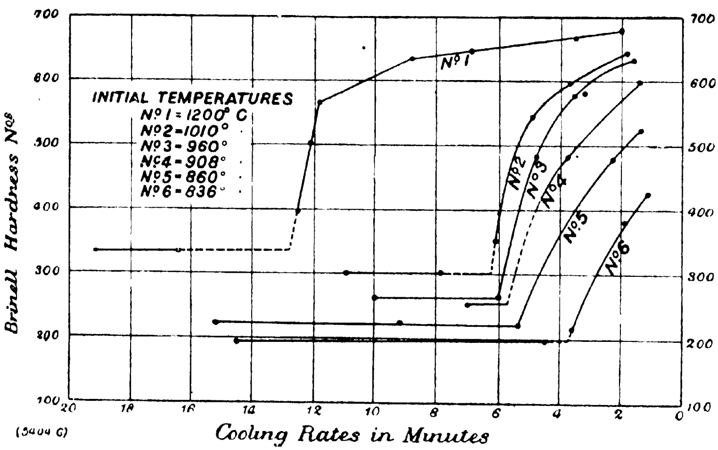


FIG. 218.—EFFECT OF INITIAL TEMPERATURE, AND COOLING RATE UPON THE HARDNESS OF CHROME STEEL.

Similarly, within certain limits, the higher the initial temperature at which cooling begins the harder will be the steel.

Fig. 218* illustrates the effects of both of these factors in the case of a chromium steel having the following composition:

Carbon	0·63 to 0·64 per cent.
Chromium	6·15 per cent.

The initial temperatures of cooling ranged from 1200° C. down to 836° C., and the rates of cooling from 2 to 20 minutes.

* "The Hardening and Tempering of Steel," Prof. C. A. Edwards, *Engineering*, March 8, 1918.

The material was heated in the form of 1 inch cubes, in an electrical furnace, and then cooled at various rates by placing in different parts inside or outside the furnace.

The maximum hardness was obtained when the steel cube was cooled in 2 minutes from 1200° C., and was about 685 on the Brinell scale.

When the cubes were cooled in air in the ordinary way from 1000° C. the hardness was 642, the specimen taking about half an hour to cool in still air upon an asbestos pad.

The hardness, when the specimen was allowed to cool for one hour in the furnace, was 281.

Heating of Objects for Hardening.

It is important for hardening work to be able to obtain an uniform temperature in the furnace, to be able to control this temperature, and to have proper means for ascertaining the correct temperature at the place where the parts are being heated. A brief description of suitable muffles and pyrometers is given later.

The principle to be adopted in heating up objects for hardening is to heat them sufficiently slowly to allow the temperature to become uniform throughout the whole mass of the objects, otherwise, if heated too quickly the surface corners and projecting parts, such as the teeth of wheels or cutters, become overheated, and when subsequently quenched, they become brittle and useless.

Another effect of too rapid heating is to cause the objects to warp, or deform, owing to the different temperatures at different parts of the objects, causing unequal expansion stresses.

It is also very important to avoid overheating steels of all kinds, as this causes oxidizing or "burning," often with the formation of slag or impurities, the strength properties are reduced and cracks or even fractures occur during the quenching operation.

The fracture of a burnt or overheated steel is white and crystalline, more particularly at the surface or edges. If the

steel is not at an uniform temperature before quenching, it is apt to crack during quenching owing to unequal contraction.

The more intricate the shape and mass distribution of the material in an object, the greater is the necessity of employing the correct temperatures, heating, and suitable quenching media.

Small objects can be effectively heated in a muffle, or smith's furnace by enclosing in a wrought-iron pipe, closed at one end, the pipe being repeatedly turned during the heating process to ensure an uniform temperature.*

Hardening Processes.

It is only possible to consider a few typical examples of hardening processes here, owing to the very large number of hardening steels now upon the market, each with its own recommended heat treatment.

The process of hardening consists in slowly and uniformly heating the part to a temperature above the critical point, and allowing the whole mass to attain this temperature, after which the part is cooled at a more or less rapid rate to a given temperature.

For the maximum hardness the most rapid cooling in a low temperature medium, which can quickly absorb, dissipate, or conduct away the heat of the steel part, is necessary; the quenching media in such cases are mercury, oil, brine, or water at about atmospheric temperature. For example, a piece of high carbon, or "cast steel," heated to about 800° C., and quickly plunged into a bath of cold water, will attain a glass-hardness, and at the same time a high tensile strength with low elongation.

Where the quenching is not required to be so violent, warm water, oil, or brine baths are employed.

In some cases the particular steel treated would be too

* Table No. CXXXIX., p. 556, gives the colours, as seen by the eye, corresponding to the different temperatures of heating, forging, hardening, and other heating processes.

brittle if quenched in the above manner; the air blast is employed in such cases as the cooling medium.

A rapid cooling effect can be obtained with mercury as the quenching medium owing to its high thermal conductivity. Very small objects such as watchmakers' drills are hardened by heating to redness and plunging into pitch or sealing wax; others are merely waved about in the air to harden.

Effect of Mass upon Hardness of Objects.

The effect of "mass," that is to say, the bulk or size of the object to be hardened, has an important bearing upon the process and the results, for large solid objects when quenched cool from the outside inwards at a given rate, whereas in the case of small objects of the same material the heat is conducted away much more quickly, and the effect of a higher cooling rate is obtained. It is therefore more difficult to correctly harden large masses, and in many cases the micro-structure and mechanical properties vary considerably from the outside to the centre.

The effects are most marked for large masses when the quenching is most drastic; for example, the results may be quoted of tests* upon exactly similar steel cubes, each of 18-inch side, heated gradually to the same uniform temperature of 900° C. throughout their whole mass, and then allowed to cool in the following ways: (*a*) upon knife-edges in air, (*b*) by plunging in oil, and (*c*) by plunging in cold water. The air-cooled cube was found to give uniform strength results throughout its whole mass.

The oil-cooled cube, which was found to cool fairly rapidly, gave a higher tensile strength and lower elongation than in the case of the air-cooled one, and these properties were fairly uniform throughout the mass.

The water-quenched cube cooled much more rapidly than the other, and the tensile strength and elongation were found to vary considerably from the centre to the outside. It was noticed that there was an important difference between the

* "The Effect of Mass," E. F. Law, Proc. Iron and Steel Institute, 1918.

cooling in oil and that in water, there being a sudden slowing up in the "cooling in oil" case in the lower ranges of temperatures as compared with the cooling in water. The time required for the centre of the cube to cool from 900° to 540° C. was almost the same in both cases, but in the cooling from 540° to 315° C. the cube in oil took nearly *twice the time*, and from 315° C. nearly *four times* as long. The differences were even greater for the outside of the cube.

It should be remembered that with large or complicated shapes in which different parts cool at different rates, internal stresses are very apt to occur, during cooling; in general, and as the above results prove, large and intricate parts should not be quenched in cold water, but in hot water, oil, or air. Fragile and large objects are frequently hardened by quenching in tallow, brine, or lime, or in warm water first, and finished in oil.

Tools, dies, and parts of complicated shape may be partially quenched in water until they have fallen in temperature to a black heat, and then plunged into hot water or oil; in this manner hardening stresses are avoided, and the risk of distortion minimized.

A method* adopted for hardening milling cutters and irregularly shaped articles, which are liable to crack or to warp, is to quench in warm water at from 30° to 38° C., or in a bath of water with an oil layer on top.

Hardening of Cast Tool Steels.

The most suitable temperatures for steels of different carbon-content for forging, annealing, and hardening are given in Table LX. upon p. 335, and in this connexion it should be emphasized that the correct forging temperature for a given steel is always higher, by some 70° to 150° C., than the hardening temperature. Tool steels after forging should first be allowed to cool slowly (or annealed), and then heated up again for hardening; they should not be forged and hardened in one operation.

* Messrs. G. P. Wall, Sheffield.

Tool steels should be slowly heated up in a closed muffle with proper heat regulation means, and should not be heated beyond the lowest temperature at which they will harden, otherwise the best results will not be obtained.

After the correct temperature for hardening has been attained the parts are sometimes withdrawn from the furnace and allowed to cool slightly before quenching.

It is advisable to take the chill off the water before quenching, leaving the water at from 15° to 25° C. for tool steels, and during quenching the part should be moved about in the water to promote better cooling.

Long slender objects, such as tubes* or rods, should be quenched in a vertical position in a warm bath.

Parts having hollow shapes, such as partially drilled objects, hollow cylindrical shapes with one end closed, hollow milling cutters, dies, and similar objects should always be quenched with the open side uppermost, in order to allow the steam to escape, otherwise it would prevent the hardening medium from coming into contact with the hollow portions of the object, and cause softness† there. In the case of objects of varying thicknesses, the thickest parts should enter the quenching medium first.

When parts are quenched they should be held, or rather moved about, in the liquid, until such time as they are quite cool; they must not be thrown in and allowed to fall to the bottom, otherwise the lower surface parts near the bottom will not cool as quickly as the other portions, and unequal cooling stresses and warping may occur.

Steel objects having holes in them are apt to crack during hardening unless carefully attended to; it is often advisable to plug holes which do not require to be hardened with soft iron rod or fireclay.

The process of hardening requires much skill and experience on the part of the individual, but the results obtained are now rendered more reliable and uniform by employing proper

* See also p. 416.

† This is the principle of a local softening process for hardened parts.

thermometric devices for temperature control and measurement.

Edge or End Hardening.

In many cases the end of an object only requires to be very hard, whilst the body is left more or less soft; examples are to be found in the cases of most cutting tools, knives, lathe and machine tools, chisels, and similar objects.

The method usually employed is to heat the end to be hardened to the proper hardening temperature, say to a cherry-red heat (760° C.) and plunge the whole object into a suitable cooling medium, the hottest part entering first. The hardness will be found to progressively diminish from the edge or end inwards.

By withdrawing when black hot from the quenching liquid and quickly cleaning with emery paper or bath brick, a series of oxide film colours will be seen to be travellling down the object, ranging from a white colour near the end through a series of yellow, straw brown, purple, and blue colours; each colour corresponds to a definite temperature* and if the object is quenched when any particular colour is at the edge or end the hardness will correspond to the temperature or colour.

The whitest colour is the hardest and strongest, and the blue colour corresponds with the softest, most ductile state. This process is in reality one of hardening and tempering combined, and the same effect would be obtained by quenching right out. and then reheating to the same colour or temperature and quenching again.

Salt Baths for Hardening and Tempering Steel.

In some cases it is found to be more convenient to heat steel objects in molten salts, and to temper other steels in such baths. Table CXXIII. gives the temperature ranges and applications of a few typical salt baths.

It may be here added that combined hardening and tempering may be accomplished with such baths.

* See Table CXXVIII., p. 512

TABLE CXXIII.

COMPOSITIONS OF SALT BATHS FOR HEATING STEELS.

Type of Steel.	*Temperature Range.*	*Composition.*
Ordinary tool steels, etc.	750° to 850° C.	Barium chloride, 3 parts; potassium chloride, 2 parts.*
High-speed steels, etc.	1050° to 1300° C.	Chemically pure barium chloride.
Ordinary steels ..	Below 750° C.	Sodium chloride, or a mixture of sodium chloride and potassium chloride (liquid at 670° C.).
Tempering steels . .	Below 580° C.	Equal parts, potassium nitrate and sodium nitrate.

Tempering.

The process of tempering, or partially softening, hardened objects consists in reheating to a certain definite temperature and quenching; the higher the temperatures of reheating, the softer will be the material, and the more nearly will it approach its annealed state.

The following is the Engineering Standards Committee's definition of tempering: Tempering means heating a steel (however previously hardened) to a temperature not exceeding its carbon change point with the object of reducing the hardness or increasing the toughness to a greater or less degree. The operation may usually be followed either by slow cooling or water-quenching without materially affecting the final result.

The effect of tempering a hardened steel is to break down the hardened state of steel, and to transform the "hardening" constituents into others corresponding with the softer conditions It should be remembered that the higher the tempering temperature, the more unstable become the transition constituents, until at the critical change points complete instability or breakdown occurs, leaving the metal in its softest condition.

The following table shows the effect of tempering 1·57 per

* For lower temperatures the amount of the latter compound should be increased.

cent. carbon steel at different temperatures, upon the constitution of the metal; it was found that the heating curve of this steel showed three accelerations, at 275° C., 400° to 500° C., and at 610° to 700° C., and the tempering temperatures were chosen accordingly:

TABLE CXXIV.

EFFECT OF TEMPERING UPON THE CONSTITUENTS OF 1·57 CARBON STEEL. (Osmond.)

Method of Heat Treatment.	*Tempering Colour.*	*Condition of Structure.*
Quenched from 1050° C. in iced water	--	Austenite with smaller amount of hardenite present as barbed streaks or laminæ, which cannot be scratched with a needle.
Quenched from 1050° C., and tempered at 275°C.	Pale yellow.	Austenite and hardenite; the latter can be slightly scratched with a needle.
Quenched from 1050° C., and tempered at 395°C.	Blue	Austenite and hardenite; both can be readily scratched with needle. Austenite residue covered with numerous spots and cleavages, parallel to needles of hardenite; greater proportion of latter.
Quenched from 1050° C., and tempered at 495°C.	Dark blue	Martensite and troosite with cementite.
Quenched from 1050° C., and tempered at 620°C.	—	Chiefly sorbite and cementite.
Annealed	—	Cementite and pearlite.

Effect of Tempering upon Strength Properties.

It is now becoming the practice for high quality steel manu facturers to supply tempering-hardness and strength curves with their steels in order to enable the user to vary the heat treatment, so as to obtain any particular strength or hardness property with the material, and to know within what limits of temperature to work to a given specification.

These charts enable the full range of usefulness of the materials to be realized.

Charts for nickel-chrome and chrome-vanadium steels are given in Figs. 168, 169, and 170, and these show clearly the

effect of the tempering temperatures upon the mechanical properties of the steels.

Fig. 219, A, B, and C,* show the effect of temperatures of tempering upon the Brinell hardness of chromium and chromium-tungsten steels of the compositions indicated in the diagrams.

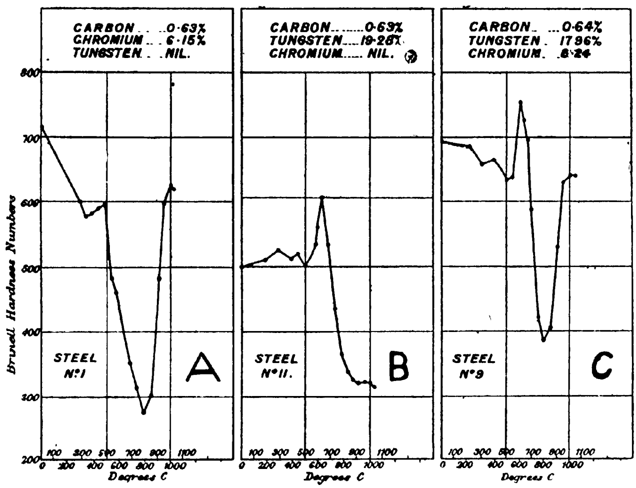


FIG. 219.—EFFECT OF TEMPERING TEMPERATURES UPON THE HARDNESS OF ALLOY STEELS.

Tempering Processes.

With a knowledge of the correct temperatures for specified strength requirements, it is possible to heat the objects in a mixture of salts, lead alloys, or oil to the desired temperature with a fair degree of accuracy. There is now a considerable number of tempering mixtures of lead and tin alloys, and of other fusible alloys, the melting points of which are known accurately, so that, unless these mixtures are over-heated after melting, it is a fairly easy matter to temper at any desired temperature. Tables CXXV., CXXVI. and CXXVII. give the melting points of different mixtures employed for tempering

* See footnote, p. 499.

baths; it will be seen that in the case of the lead-tin mixtures, that the melting point increases with the proportion of lead. The melting point of lead is 327° C., and of tin 232° C., that of bismuth being 269° C., antimony 630° C., and zinc 418° C.

TABLE CXXV.

Melting Points of Alloys.

Percentage Composition.			*Melting Point ° C.*	*Percentage Composition.*			*Melting Point. ° C.*
Tin.	*Lead.*	*Bismuth.*		*Tin.*	*Lead.*	*Bismuth.*	
18·8	31·2	50·0	94	50·2	33·2	16·6	158
17·7	35·5	47·0	98	48·0	36·0	16·0	155
15·8	42·1	42·1	108	45·9	38·8	15·3	154
20·0	40·0	40·0	113	45·0	40·2	14·8	153
27·0	36·5	36·5	117	43·0	43·0	14·0	154
33·3	33·3	33·3	123	41·5	44·8	13·7	160
30·8	38·4	30·8	130	40·2	46·6	13·3	165
28·5	43·0	28·5	132	38·2	49·0	12·8	172
25·0	50·0	25·0	149	37·5	50·0	12·5	178
29·5	47·0	23·5	151	41·5	46·8	11·7	167
33·4	44·4	22·2	143	43·0	45·6	11·4	165
57·0	42·0	21·0	143	44·4	44·4	11·2	160
40·0	40·0	20·0	145	46·0	43·2	10·8	159
43·0	38·0	19·0	148	47·5	42·0	10·5	160
45·7	36·2	18·1	151	49·8	41·0	10·0	161
48·1	34·6	17·3	155	50·0	40·0	10·0	162

TABLE CXXVI.

Melting Points of Lead-Tin Alloys.

Composition.		*Melting Point ° C.*	*Composition.*		*Melting Point ° C.*
Lead.	*Tin.*		*Lead.*	*Tin.*	
100	0	327 (pure lead)	32·5	67·5	180 (lead-tin eutectic*)
90	10	290			
80	20	265	30	70	182
70	30	250	20	80	195
60	40	235	10	90	210
50	50	218	0	100	232 (pure tin)
40	60	200			

* Lowest melting point of the lead-tin series.

TABLE CXXVII.

MELTING POINTS OF LEAD-ANTIMONY ALLOYS.

Composition.		Melting Point ° C.	Composition.		Melting Point ° C.
Lead.	*Antimony.*		*Lead.*	*Antimony.*	
100	0	327 (pure lead)	60	40	356
			50	50	402
90	10	250	40	60	448
87	13	228 (lead-antimony eutectic)	30	70	493
			20	80	539
			10	90	582
80	20	260	0	100	630 (pure antimony)
70	30	310			

Lead baths are frequently employed for tempering steel articles, the objects being placed in the lead bath after a preliminary warming up; the temperature of the molten lead can be raised from 327° C., its melting point, to most of the tempering temperatures required in practice; it is not of course suitable for hardening steels.

Precautions Necessary.

It is necessary to prevent the lead from sticking to the metal objects by coating them with any of the pastes available for the purpose.

The following materials are recommended* for this purpose:

(*a*) Soft soap.

(*b*) Saturated salt water solution.

(*c*) Blacklead and water paste.

(*d*) Pulverized charred leather, 1 pound; fine flour, 1½ pounds; 2 pounds fine salt; mix together and water gradually to a varnish consistency.

It is necessary to thoroughly dry the coated parts before placing in the lead bath.

The lead bath must be kept stirred, otherwise the lower parts become hotter than the top, owing to heat conduction. The objects after heating for a period depending upon their

* Messrs. G. P. Wall, Sheffield.

size and shape, but usually varying from one to three hours, should be cleaned from any lead adhering with a wire brush (otherwise soft spots will occur), and quenched or cooled in water which is free from acids or alkalies. Charcoal in powder form is used for sprinkling over the surface of the lead, to prevent the dross formation; the lead itself must be pure and free from arsenic and sulphur. Many objects, where suitable for the method, are simply cleaned and tempered by heating of a "heating plate"* until the desired temperature, as indicated by the colour of the oxide film, is attained, and quenched.

Small objects are sometimes tempered in a hot sand bath provided with a pyrometer.

Change of Volume due to Hardening and Tempering.

The specific gravity of steel varies with its hardness, or in other words with the nature of the heat treatment process.

In general, the volume is increased by hardening and reduced by subsequent tempering. Thus on hardening steel bars 4 inches long by $\frac{7}{8}$ inch diameter, the length was found† to increase by from 0·0001 to 0·0014 inch, and the diameter by 0·0003 to 0·0036 inch.

On tempering, the length decreased 0·0017 to 0·0108 inch as compared with the original 4 inches, and the diameter was increased 0·0003 to 0·0029.

The changes in volume of case-hardened steels is considered on p. 525. In the case of high-speed tungsten-chromium steel the following values were obtained.‡

Tempering Temperature ° C.	0	100	200	300	400	500	600	700	800
Brinell Hardness..	700	680	670	655	650	640	750	500	400
Specific gravity ..	8·67	8·685	8·680	8·688	8·680	8·690	8·620	8·640	8·660

* Heating plates should be gas-heated and under complete temperature control.

† J. E. Storey, *Amer. Mach.*, February 20, 1908.

‡ Prof. C. A. Edwards.

TABLE CXXVIII.

TEMPERING COLOURS AND TEMPERATURES.

Colour.	° *C.*	° *F.*	*Temperature Suitable for Tempering—*
Dark blue . .	300	572	Springs; wood saws.
Full blue . .	295	563	Circular saws for metal; screw-drivers.
Very dark purple	290	554	Cold chisels for iron; needles.
Dark purple . .	285	545	Moulding and planing cutters for soft wood; cold chisels for cast iron; firmer chisels.
Full purple . .	280	536	Bone and ivory saws; cold chisels and setts for steel gimlets.
Light purple . .	275	527	Axes, hot setts and adzes; dental and surgical instruments, pressing cutters.
Brown purple	270	518	Augers; flat brass drills; twist drills; coopers' tools.
Reddish brown	265	509	Wood boring tools; stone cutting tools.
Yellowish brown	260	500	Plane irons, gauges; planing and moulding cutters; punches and dies; cups, snaps, and shear blades.
Yellow brown	255	491	Planing and moulding cutters for hard wood; penknives, chasers.
Very dark yellow	250	482	Taps; mill chisels and picks; screw-cutting dies; rock drills.
Dark yellow . .	245	473	Boring cutters; leather cutting dies; reamers.
Dark straw . .	240	464	Milling cutters, bone cutting tools; drills; wood-engraving tools.
Straw . .	235	455	Iron planers; paper cutters; ivory cutting tools; steel planers.
Pale straw . .	230	446	Hammer faces, brass screwing dies.
Light straw . .	225	437	Light turning tools, steel-engraving tools.
Very light straw	220	428	Scrapers, lathe tools for brass.

Case-Hardening.

Case-hardening consists in giving to a low carbon content, mild, or low carbon alloy steel, an extremely hard surface, or case, by carburizing, or increasing the carbon content of the surface to from 0·90 to 1·10 per cent.* This process enables parts to be readily machined prior to hardening, but to possess high wearing endurance, combined with a tough and ductile core; it avoids the brittleness of certain of the hardened high carbon and alloy steels, whilst retaining a surface hardness of equal quality.

The process of case-hardening consists in packing the parts in air-tight iron boxes, filling all vacant spaces with a suitable

* Recommended for the best results.

carburizing mixture—that is, a mixture rich in carbon, such as charcoal, bone-black, leather, horn-parings, etc.—and heating the whole to a temperature of about 875° to 950° C., at which temperature they are maintained for a period varying from four to twelve hours, according to the depth of case required.

The articles are then either quenched upon withdrawal from the box in cool water, or are allowed to cool down in the box, then reheated to 750° to 780° C. and quenched, or reheated twice and quenched first, at about 800° to 820° C., and, secondly, at from 750° to 780° C.; the particular procedure adopted depends upon the purpose for which the part is required.

Theory of Case-Hardening.

Considering the case of a mild carbon steel, it is evident that when a temperature of about 900° C. is attained the constitution of the steel will have become a homogeneous solid solution of carbide of iron in iron. For each carbon content steel there is a definite minimum temperature, above which the carbide of iron passes into solution with the iron; generally speaking, for the low and medium steels the higher the carbon content, the lower will be the temperatures of solution. Table CXXIX. shows the approximate temperatures of solution for carbon steels of different carbon content.

TABLE CXXIX.

Temperatures at which Ferric Carbide passes into Solution in Iron for Carbon Steels.

Percentage of carbon ..	0·15	0·30	0·50	0·60	0·70
Temperature ° C. ..	885	830	780	765	750
Percentage of carbon ..	0·90	1·00	1·10	1·20	—
Temperature ° C. ..	740	780	820	860	—

As the percentage of carbon increases from 0·90 the formation of free cementite occurs, and the temperature again rises.

In the case of a low carbon content steel, at about 900° C.* the solution of carbide of iron in iron is a dilute one, capable of taking up or of dissolving much more carbon or carbide of iron than it originally contained. If, then, this steel is placed in contact with a suitable carburizing agent, whether solid, liquid, or gaseous, carbide of iron is formed therefrom, and is dissolved and diffused into the steel; it is now generally believed that the chief agents in affecting carburization are the carbon containing gases such as carbon monoxide and carbon dioxide, generated within the carburizing medium.

The carbon content of the "case" can be controlled to a large extent by regulating the cementation temperature and the composition of the carburizing medium, whilst the depth of the case is governed by the period of time during which the cementation temperature is maintained. For any given steel, these factors must be determined by experience, or by making preliminary tests.

When the steel has been in the carburizing medium for a sufficient length of time, it will consist of an outer case, or shell, of a solid solution rich in carbon, and an inner core of solid solution low in carbon; if the process has been properly carried out, there will be a gradual transition from one to the other.

If the steel is now allowed to gradually cool down, it will be found to consist of an outer shell of pearlite or pearlite and cementite, with an inner core of ferrite and pearlite, the former being in excess. The ferritic structure of the core is left rather coarse by the carburizing operation, so that it is advisable to reheat the articles to a temperature of about 850° to 900° C., and to cool them from this temperature; this process is somewhat analogous to normalizing, for it refines the structure by diminishing the size of grain.

The Structure of Case-Hardened Steel.

The next operation—namely, that of hardening the carburized steel part—consists in a single or double quenching from a pre-

* Termed the "*cementation temperature.*"

determined temperature, and it leaves the steel in the condition of possessing a ferritic or ferritic-and-pearlitic core, or interior, with an outer case, or shell, of pearlite and cementite.

The structure of a case-hardened mild steel can be examined microscopically, and it can at once be seen whether the case is rich or poor in carbon, and to what depth it has penetrated. Fig. 220 shows a typical micrograph of case-hardened mild steel.

A convenient method* for examining this steel is to polish in the usual manner, after heating in charcoal powder to about

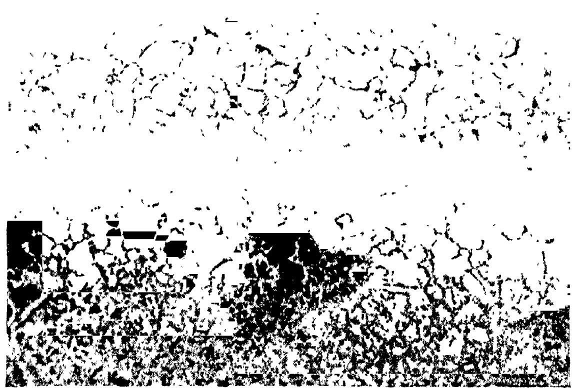


FIG. 220.—MICROPHOTOGRAPH OF CASE-HARDENED MILD STEEL. × 25.

760° C. (just above the recalescence point) and allowing to cool slowly; this process will not carburize the metal but will convert the carbon of the hardened steel into the pearlitic condition. By etching, after polishing, with a strong acid, the depth of the carburized layer and the approximate carbon content may be readily ascertained. Alternatively the specimen may be ground at right angles to the surface, polished. and acid-etched, when the high carbon, or hardened layers, will appear as dark portions gradually merging into the lighter parts of low carbon steel, as shown in Fig. 220.

* Osmond.

Effect of Time and Temperature upon Depth of Penetration of Carbon.

The subject of the diffusion of carbon into iron and mild steel has been studied by many authorities; it will suffice here to quote from some of the results of Guillet's* researches.

He found that in the case of both steel and iron the depth of penetration of the carburizing carbon was the same, when both were subjected to eight hours' treatment at 1000° C., although the steel contained 0·5 per cent. carbon.

The *effect of time* upon the depth of carbonization for iron heated at 1000° C. is shown by the following table:

TABLE CXXX.

EFFECT OF CARBURIZING PERIOD UPON DEPTH OF CARBON LAYER.

Time.	*Depth of Penetration.*	*Time.*	*Depth of Penetration.*
Hours.	*Mm.*	*Hours.*	*Mm.*
½	0·5	4	1·3
1	0·8	6	2·0
2	1·0	8	3·0

The *effect of temperature,* when iron was carburized for eight hours is shown by the following results:

TABLE CXXXI.

EFFECT OF CARBURIZING TEMPERATURE UPON DEPTH OF CARBON LAYER.

Temperature, ° C.	*Depth of Penetration.*	*Temperature, ° C.*	*Depth of Penetration.*
	Mm.		*Mm.*
800	0·5	950	2·8
850	1·0	1000	4·2
900	1·6	1050	5·2
925	2·0		

* "Memoires de la Société des Ingenieurs Civils de France," 1904, p. 177.

Temperatures and Processes of Hardening.

When the initially carburized part is reheated to about 730° to 750° C. the whole of the case, or shell, together with the pearlitic areas of the core, will attain the solid solution state. This is a very suitable condition to quench in, as it gives hardened case with a minimum section of area of hardened material in the core.

If the temperature be raised to 800° C., the whole of the core will have become a homogeneous solid solution capable of being hardened, so that if quenched in this condition the core will be much tougher and harder, and will consist of a matrix of hardened steel with soft iron "inclusions," whereas in the former case it will consist of a matrix of soft ferrite with hardened steel "inclusions."

It will thus be evident that the mechanical properties of the core will vary widely with the quenching temperature. If the hardening temperature is too low, "soft spots" in the parts will be apt to occur, due to a local breaking down of the solid solution state.

Table CXXXI.A shows the properties* of a low carbon steel, in different conditions, of the following composition:

Carbon	0·17 per cent.
Silicon	0·08 ,,
Sulphur	0·053 ,,
Phosphorus	0·056 ,,
Manganese	0·85 ,,

The case-hardening processes upon this material in the form of 1-inch bars, carburized for about two and a half hours in a box, are indicated in the table, but it may be added that in Condition A the carbide in the case and core can dissolve at the temperature stated (900° C.), provided that a large excess of cementite is not present, but the case becomes overheated and is therefore crystalline, as shown by the high tensile strength.

The structure in Condition B is refined, due to the reheating after quenching, whilst in Condition C the core becomes norma-

* "Commercial Steels and their Heat Treatment," J. B. Hoblyn. Proc. Inst. Aut. Engrs., May, 1918.

TABLE CXXXI.A.

PROPERTIES OF MILD CARBON STEEL IN DIFFERENT CASE-HARDENED CONDITIONS.

Condition of Material and Treatment.	*Yield Point, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Reduction of Area per Cent.*	*Yield Ratio.*	*Izod Impact Value, Foot-Pounds.*	*Scleroscope Value on Case.*	*Brinell Hardness in Core.*
As rolled	27	35	36	63	77	—	—	158
Normalized	20	31	37	65	64·5	—	—	149
A. Carburized for 2½ hours, cooled in the box, reheated to 900° C., and quenched in water. Case ground away for the test piece.	37·0	52·0	22·6	51·8	71·3	36	90 to 100	302
B. Cooled in the box after carburizing, then reheated to 900° C. and quenched, then reheated to 770° C. and quenched. Case ground away.	29·8	41·7	35	64·5	71·5	93	92 to 100	201
C. Cooled in the box, normalized from 900° C., and reheated to 770° C., and quenched in water. Case ground away.	29·6	41·7	29·9	54·5	70·8	30	90 to 100	201

lized, due to the slow cooling from 900° C. in air, and the reheating to 770° C. refines the case.

Condition B, which is obtained by the process of double quenching, is the one which is usually recommended in practice, the material then being in about the most satisfactory condition.

If the cementation temperature be too high, the case will be found to contain a high carbon content, and will be harder, but more brittle.

Fig. 221* shows some typical fractures of case-hardened mild steel, the depth of the casing being clearly illustrated.

It is advantageous to temper case-hardened parts in oil at about 120° C., in order to relieve quenching stresses.

The following methods of heat-treating case-hardened parts are recommended† for the purposes stated:

1. *For Parts not subjected to Shocks.*—Quench the parts immediately on withdrawal from the box. Reheat to a cherry-red (780° C. or 1436° F.) and quench again. This reheating and quenching refines the surface.

2. Allow the boxes to cool, then take out the parts and reheat to a cherry-red (780° C. or 1436° F.) and quench.

3. *For Maximum Strength and Toughness.*—Allow the articles to cool in the boxes, then take them out, and reheat to a full cherry-red (810° C. or 1490° F.) and quench. Reheat to 760° to 780° C. (1400° to 1436° F.) and quench again.

4. For articles that are liable to warp, the following modification in the previous treatment may be made:

Allow the parts to cool in the boxes, reheat to a bright red (900° C. or 1652° F.), and allow to cool in air, then reheat to 760° to 780° C. (1400° to 1436° F.) and quench. Oil-quenching is often substituted for water-quenching, but the case obtained is not so hard, although the risk of distortion is lessened.

Case-Hardening Methods.

The articles to be case-hardened should be well packed with the carburizing materials in air-tight iron boxes, using fire-clay to make the joints tight.

* Messrs. Vickers, Ltd. † Messrs. G. P. Wall, Sheffield.

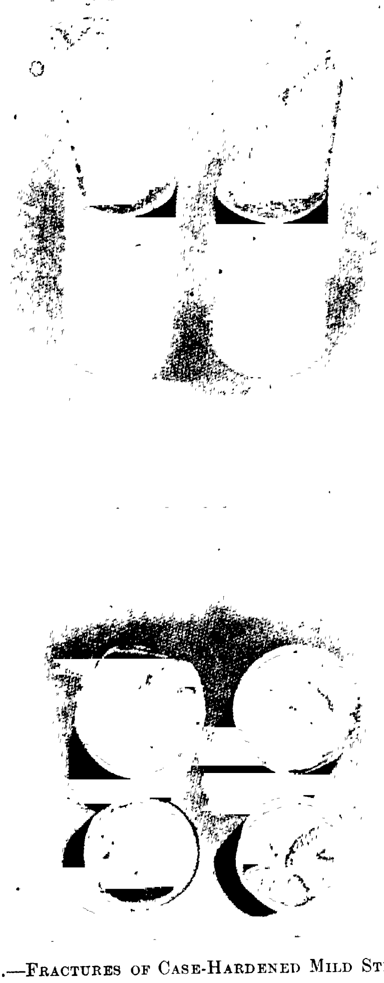


FIG. 221.—FRACTURES OF CASE-HARDENED MILD STEEL BARS.

The bottom of each box should be covered to a depth of at least 1 inch with the carburizing material; the articles should then be placed in rows with at least 1 inch space between each article, and between the articles and the sides of the box. The

whole space between the parts and the sides of the box should then be filled with carburizing material; several layers of articles may be employed.

The most usual carburizing period is from four to six hours, the time being taken when the boxes and contents have reached the correct cementation temperature; the usual temperature is about 900° C.

The progress of the carburizing process may be ascertained by inserting test wires of the same material as the parts through the lids of the boxes; these wires are withdrawn at intervals and quenched or heat-treated in the same manner as the articles are finally treated. The fractures of these wires are examined microscopically, and the depth of carbon penetration observed.

Influence of Furnace "Atmosphere."

It is of great importance to prevent oxidation of the heated parts, which would, of course, cause decarbonization of the metal; for this reason the ingress of air should be prevented to the casing boxes.

The most successful case-hardening processes employ a reducing atmosphere, in which the articles are in contact with gases, such as carbon monoxide or dioxide, either stationary or passed along as a gas-stream. In the latter case, the period of the process is appreciably reduced.

Influence of Manganese, Nickel, etc.

It is well known that the presence of manganese in steel is beneficial in removing or reducing the effects of sulphur and phosphorus, by deoxidizing them, but the manganese should not be present in more than 0·5 per cent., otherwise, apart from its deoxidizing properties, it lowers the impact value of the steel. The amount of sulphur present should be as small as possible.

The effect of nickel in a steel is to lower the temperature at which the carbide of iron goes into solution with the ferrite, or iron, and also to lower the temperature at which it separates

out of solution. For this reason cementite does not form so readily in the case, as with carbon steels, and, further, during the cooling of cemented parts, the ferrite in the core must be cooled to a much lower temperature before it can throw out the carbide in solution during the cementation process. Thus, instead of the usual 900° C. required for mild steel, a temperature of only about 740° C. is required for the carbide in 3 per cent. nickel steel of low carbon content to pass into solution.

Nickel case-hardening steels are therefore usually found to give a better gradation from the case to the core than with carbon steels, and as there is a reduction in the amount of the free cementite present, the case is not so brittle, and the parts themselves can withstand shock much better.

Table CXXXII. gives the mechanical properties* (when carburized and treated as specified) of a 3 per cent. case-hardening nickel steel of the following composition:

Carbon	0·10 per cent.
Silicon	0·15 to 0·20 per cent.
Sulphur	0·025 ,,
Phosphorus	0·025 ,,
Manganese	0·50 ,,
Nickel	2·8 to 3·2 ,,

Case-Hardening Mixtures.

For thin cases, for iron and mild steel, the parts are heated to about 900° C. (full to bright red heat) and sprinkled with, or plunged into, a finely powdered mixture of one or other of the following mixtures, reheated for a short time to enable the mixture to melt and run, and finally plunged into cold water.

(*a*) Potassium cyanide.
(*b*) Potassium ferrocyanide.
(*c*) Potassium ferrocyanide and potassium bichromate.
(*d*) Sodium ferrocyanide, 90 parts; anhydrous sodium carbonate, 10 parts.

The case obtained with these materials is very hard, but not very deep.

* J. B. Hoblyn.

TABLE CXXXII.

PROPERTIES OF 3 PER CENT. NICKEL CASE-HARDENING STEEL UNDER DIFFERENT HEAT TREATMENT CONDITIONS.*

Condition or Treatment.	*Yield Point, Tons per Square Inch.*	*Tensile Strength, Tons per Square Inch.*	*Elongation per Cent.*	*Reduction of Area per Cent.*	*Yield Ratio.*	*Impact Value, Foot-Pounds.*	*Hardness. on Case.*
Normalized	20	30	34	62	0·66	—	130 to 140†
A. Heated to 900° C., after carburizing, and quenched in water. Reheated to 720° C. and quenched in water.	29·0	39·3	33·9	64·1	0·74	68	95 to 100
B. Heated to 820° C. and quenched in water, then reheated to 720° C. and quenched in water.	33·7	42·5	32·2	64·5	0·79	70	95 to 101
C. Heated to 760° C. and quenched in water.	39·2	49·1	24·3	59·6	0·80	48	98 to 101
D. Heated to 850° C. and cooled in air to normalize, then reheated to 720° C. and quenched in water	27·1	40·0	31·1	57·0	0·68	43	95 to 100

* In all cases the tests refer to the cores of 1 inch bars treated in the manner indicated.

† Brinell No., the other values being Scleroscope Nos.

For more deeply carburized parts the following materials are suitable:

(*e*) Wood charcoal.
(*f*) Animal charcoal (bone).
(*g*) Leather, bone, and horn parings crushed.
(*h*) Lamp black and bone black.
(*i*) Barium carbonate, 40 per cent.; charcoal, 60 per cent. (Guillet's mixture).
(*j*) Wood charcoal, 95 per cent.; soda ash, 5 per cent.
(*k*) Wood charcoal, 90 per cent.; common salt, 10 per cent.

Table CXXXIII. shows the relative carburizing merits of different materials* as expressed by the ratio of the total volume of the case to that of the initial volume of the material.

TABLE CXXXIII.

RELATIVE CARBURIZING MERITS OF DIFFERENT MATERIALS.

Material.	Ratio $\frac{\textit{Total Case Volume}}{\textit{Volume of Mixture}}$.
1. Anthracite, 75 per cent; oil, 25 per cent. ..	0·0000
2. Anthracite, 95 per cent.; potassium carbonate, 5 per cent.	0·0042
3. Coke soaked in 10 per cent. aqueous solution of potassium hydrate.	0·0048
4. Anthracite soaked in 10 per cent. aqueous solution of potassium hydrate.	0·0061
5 Anthracite, 90 per cent.; calcium cyanamide, 10 per cent.	0·0109
6. Crushed bone	0·0122
7. Anthracite, 90 per cent.; bone black, 10 per cent.	0·0138
8. Wood charcoal	0·0140
9. Charcoal, 90 per cent.; crushed bone, 10 per cent.	0·0262
10. Wood charcoal, 90 per cent.; calcium cyanamide, 10 per cent.	0·0331
11. Wood charcoal, 90 per cent.; crushed bone, 10 per cent.	0·0368
12. Bone black	0·0405
13. Leather charcoal	0·0405
14. Wood charcoal, 90 per cent.; bone black, 10 per cent.	0·0451
15. Charcoal soaked in 20 per cent. caustic potash, 90 per cent.; crushed bone, 10 per cent.	0·058
16. Wood charcoal impregnated with soda ash	0·116

* "Some Recent Improvements in Case-Hardening Practice," H. L. Heathcote, *Journ. Iron and Steel Institute*, May, 1915.

Potassium and sodium carbonate is found to restore the carburizing properties of exhausted charcoal, and mixture No. 16 is probably most efficacious in this respect.

Carburizing in Gases.

Articles can be case-hardened by heating them in a gaseous medium to the proper temperature; the gases employed should, of course, contain carbon. Typical examples of gases which have been used are acetylene, coal gas which has been freed from sulphur by bubbling through carbon disulphide, and petroleum vapour. The results of tests upon ¼-inch rods heated for about an hour at 880° C. in pure acetylene gas showed that the acetylene was completely decomposed, the carbon being deposited upon the specimen; the thickness of the case was 0·0064 inch after three-quarters of an hour. With a mixture of 1 volume acetylene and 12 volumes coal gas the specimen, after an hour's exposure at 880° C., was found to be coated with carbon and to have a case of 0·0147 inch thick.

Carburizing in Liquids.

Steel may be case-hardened by heating it in a bath of an appropriate salt, such as potassium cyanide, to a temperature of from 870° to 900° C. The cases obtained are usually very hard but are not very deep.

Change of Volume after Case-hardening.

The constitutional changes in mild steel caused by the case-hardening treatment are attended with certain physical changes, one of which is a small increase in the volume after case-hardening—that is to say, a diminution in the specific gravity. Parts required for accurate work, such as fine limit work, plugs, gauges, etc., must be ground after hardening, and allowances must be made for this specific gravity effect. The following values were obtained with a case-hardening mild steel:

	Specific Gravity.
In normalized state	7·879
Quenched from 900° C. in water	7·833
Quenched from 900° C. and 760° C. in water ..	7·861

The increase in volume in the latter case is about 0·237 per cent.

Local Hardening of Steel Parts.

In many cases, certain parts only of an article, such as those subjected to wear, abrasion, or blows, require to be hard, with the rest of the material soft. There are several methods available for realizing this result.

Messrs. Vickers, Ltd., have patented a process for hardening the wearing parts only of gear wheel teeth and similar objects, so that there is no risk of warping or inaccuracy such as often occurs with mass hardening. The method consists in drawing

FIG. 222.—FRACTURE OF LOCALLY CASE-HARDENED STEEL BY THE OXY-ACETYLENE PROCESS.

the exceedingly hot flame of a suitably constructed oxy-acetylene blowpipe across the tooth face or other surface. The temperature of the flame is so high that the surface of the steel, to a depth of from $\frac{1}{16}$ inch to $\frac{1}{32}$ inch as desired, is at once raised to the hardening temperature. As the flame passes along there is an equally rapid fall of temperature due to the absorption of heat from the hot part, by the cool remainder of the tooth, with the result that a dead hard skin is formed with no distortion effects.

Carbon steels may be locally hardened by covering parts to be left soft with a thin metal shield in iron or steel of about 28 S.W.G., so that upon quenching steam is formed between

the shield and the metal, which prevents the cooling medium from reaching the metal beneath the shield. Alternatively a pad of fireclay or asbestos, held on with iron wire, may be used.

In case-hardening processes, parts which require to be left soft for machining, etc., should be covered with iron or steel plates or asbestos pads, or the "areas of softness" may be plated with copper or nickel before case-hardening; it has been found that the carburizing material will not penetrate such plated areas.

Another method is to leave portions of the articles to remain soft rather fuller, by $\frac{1}{16}$ inch to $\frac{1}{8}$ inch, than the finished size, and to grind off these parts after carburizing. This removes the high carbon material, and the article then may be reheated and quenched in the usual manner.

CHAPTER IX

HEAT TREATMENT FURNACES

Furnaces for Heat Treatment Processes.

It may be of some interest to describe a few of the more common types of furnaces employed for the heat treatment of metals, as distinct from ore-smelting and metallurgical processes.

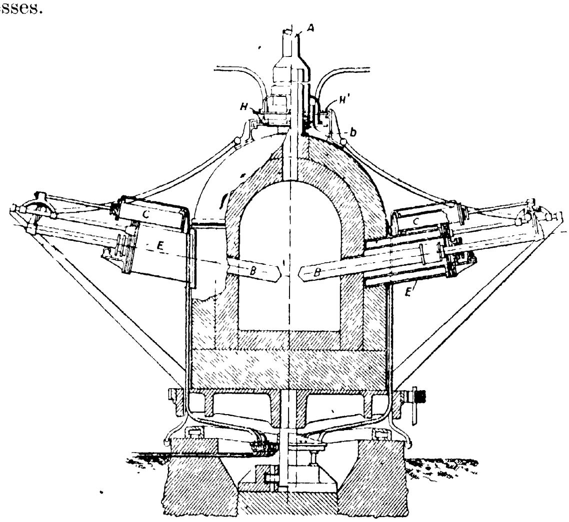


FIG. 223.—THE STASSANO ELECTRIC FURNACE USED FOR STEEL FOR CASTINGS, ETC.

BB, electrodes; *CC*, hydraulic gear for regulating position of electrodes; *EE*, water jackets for cooling electrodes; *A*, funnel for waste gases.

The types of furnace commonly employed for heat treatment processes are known as the "muffle" or "oven" type, and may be heated either with oil, gas, or coke with natural or pressure air-draught; in some cases electrical furnaces are employed tor these processes.

The muffle type of furnace is employed for heat treatment processes, such as annealing, normalizing, hardening, forging, tempering, reheating, case-hardening, steel frame bending, and similar purposes. Electrical furnaces are now finding increasing favour for melting and other metallurgical processes; this branch of the subject is, however, outside of the scope of the present work; a typical furnace is illustrated, however, in Fig. 223.

TABLE CXXXIV.

HEATING VALUES OF VARIOUS SOLID FUELS.

Fuel.	*Fixed Carbon, Per Cent.*	*Ash, Per Cent.*	*Hydrogen, Per Cent.*	*B.T.U.'s per Pound, Dry.*
Anthracite	93·0	4·00	3·00	15,000
Welsh coal (good quality) ..	87·3	3·06	4·06	15,200
Welsh smokeless navigation ..	80·0	3·40	4·04	13,960
Welsh (average quality)	76·0	3·00	4·65	14,140
Scotch navigation	70·6	2·60	4·8	13,760
Bituminous, Nottingham ..	57·1	8·00	5·11	13,000
Coke, foundry	90·0	7	0·5	13,500
Coke gas, broken and graded ..	88·0	8	0·5	13,100
Charcoal, from wood	100	—	—	12,000
Wood (average)	—	—	—	6600
Peat	—	—	—	7000 to 9000

Tables CXXXIV., CXXXV., and CXXXVI. give the heating values, expressed in British Thermal Units, of the various kinds of fuel that it is possible to employ for industrial processes; the relative merits of the different fuels depend also upon their cost, availability, convenience, initial plant cost and upkeep, and other factors.

As regards the use of coal for furnace heating purposes, it may be of interest to note that in average practice it requires about 6 to 8 hundredweight of coal to melt one ton of steel, and for coke, from 8 to 11 hundredweight.

For comparisons of different kinds of fuels, based upon their cost, it is useful to remember that in the best practice 9 million B.T.U.'s are required to melt one ton of steel, and in the average practice about a 25 per cent. higher number.

TABLE CXXXV.

Heating Value and Density of Fuel Oils.

Name of Oil.	Composition per Cent.					Gravity, Degrees Baume.	Density, Pounds per Gallon.	Calorific Value, B.T.U.'s per Pound.	Vaporizing Temperature, ° C.
	Carbon.	*Hydrogen.*	*Oxygen.*	*Nitrogen.*	*Sulphur.*				
Fuel oil	84·35	11·33	2·82	0·60	0·90	26 to 28	7·3	18,350 to 19,350	55
Californian crude oil	81·52	11·01	—	6·92	0·55	12 to 36	7·6	18,460 to 18,980	110
Mexican crude oil	83·83	12·19	0·43	1·72	2·83	12 to 23·8	7·82	18,490	79
Caucasian light crude oil ..	86·3	13·6	0·1	—	—	—	8·84	22,000	—
Caucasian heavy ditto ..	86·6	12·3	1·1	—	—	—	9·38	20,140	—
Petroleum refuse	87·1	11·7	1·2	—	—	—	9·38	19,830	78
Petrol (average)	84·0	16·0	—	—	—	—	7·20	19,500	78
Paraffin	85·0	15·0	—	—	—	—	8·7	18,900	—
Alcohol	52·2	13·0	34·8	—	—	—	7·9	12,600	80
Benzol	92·3	7·7	0	—	—	—	8·3	18,100	—

TABLE CXXXVI.

HEATING VALUES OF DIFFERENT GASES.

Name of Gas.	Composition per Cent.					Calorific Value, B.T.U.'s per Cubic Foot.
	Carbon Mon-oxide.	Hydrogen.	Marsh Gas.	Heavy Hydro-carbon.	Carbon dioxide, Nitrogen, etc.	
Illuminating or coal gas	9·0	47·0	3·4	5·0	5·0	690
Water gas	50·0	50·0	–	– –	—	350
Generator gas ..	34·3	—	—	– –	65·7	130
Siemens gas ..	20·0	6·0	1·0	1·0	72·0	130
Generator water gas	38·0	12·0	—	—	50·0	180
Mond gas	13·5	24·8	2·5		46·0	130 to 190
Coke oven gas ..	—	Combustibles	96·5	—	3·5	430 to 550
Oil gas	—	Combustibles	97·0	—	3·0	850
Blast furnace gas ..	—	—	– –	—	—	100

Theoretically only $1\frac{1}{4}$ million B.T.U.'s are necessary, but this ideal is not attainable owing to the thermal losses in the furnace, such as by radiation and conduction, imperfect combustion, etc.

Gas Furnaces.

The use of coal gas, either with natural or forced air draught, is finding increased favour, for muffle-furnaces, on account of its cleanliness, economy, labour-saving, and ease of control, or heat regulation.

When the natural draught principle is adopted, the best results are obtained from the reverberatory or *regenerative* type of furnace, in which the air supply for combustion is preheated.

Fig. 224 illustrates one of the Richmond* natural draught gas heated regenerator oven furnaces, which is suitable for reheating, annealing, hardening, and similar work. It will be

* The Richmond Gas Stove and Meter Co., Warrington.

seen that there are two ovens, the upper one being heated by the waste products from the lower one, so that two different temperatures are maintained. The temperature of the lower, or finishing, oven can be raised up to 1300° C., but the usual temperatures of 800° C. for this oven, and 500° C. for the upper oven, can be attained in about an hour from the cold. The air

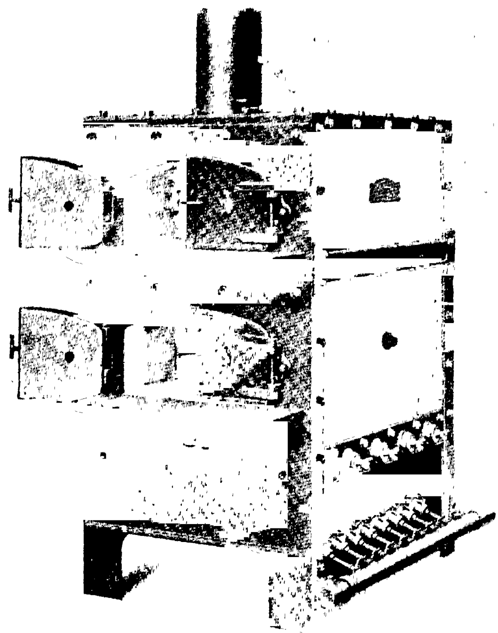


FIG. 224.—RICHMOND LOW PRESSURE GAS-AND-AIR TYPE FURNACE.

and gas supplies are each separately controllable, and the furnaces can be worked with a reducing atmosphere for annealing and similar purposes.

The sizes of these furnaces vary from 18 inches deep × 18 inches wide × $9\frac{1}{2}$ inches high, up to 63 inches deep × 36 inches wide × 18 inches high, inside oven dimensions.

A smaller model of this type of furnace is manufactured, fitted with one oven only, measuring about 14 inches deep × 12 inches wide × 9 inches high, for small workshop or motor garage requirements. This furnace will attain a temperature of 850° C. in about an hour from the cold, and a maximum temperature of 1100° C.; it is especially suitable for case-hardening, annealing, hardening, and tempering small automobile and aircraft parts.

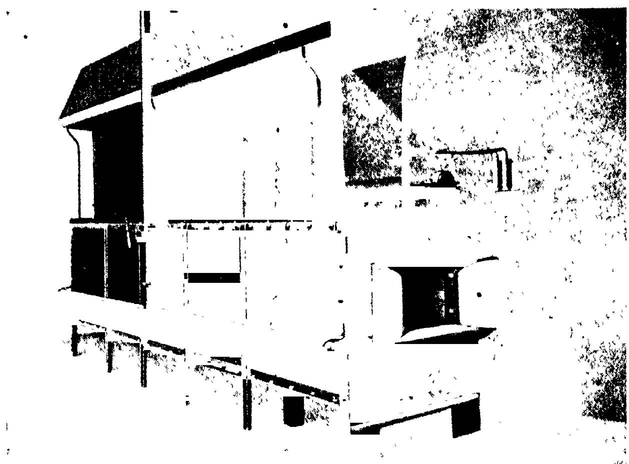


FIG. 225.—RICHMOND LOW PRESSURE GAS-AND-AIR LONG OVEN.

Higher furnace temperatures may be obtained by employing a low or high pressure air draught.

Fig. 225 illustrates a large low-pressure gas-and-air furnace, which is suitable for annealing long bars, wires, rods, tubes, and similar objects; the air pressure for this class of furnace is about 2 inches of water, the air being supplied from a fan. Maximum temperatures up to about 1400° C. can be attained in this type. The lengths vary from about 12 to 16 feet, with corresponding widths of from 2 to 4 feet, and heights of from 1 to 2 feet.

Figs. 226 and 227 illustrate the "Richmond" gas-and-air

blast furnace for heat-treating high-speed steel tools, cutters, and small parts in general. The air blast is not preheated, but is supplied at a pressure of about 1 pound per square inch. The furnace chamber is circular in shape and is heated by means of the gas-and-air blast burners, two of which are used, one at the top and one at the bottom of the chamber; the

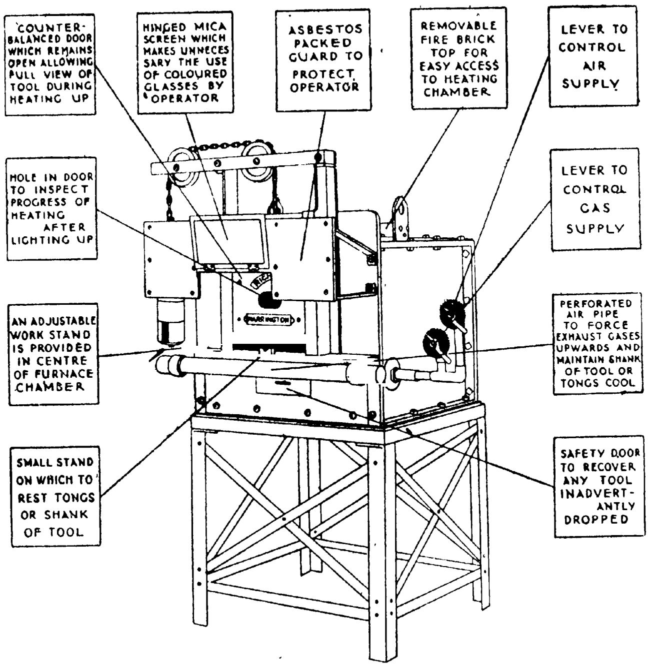


FIG. 226.—RICHMOND GAS-AND-AIR BLAST FURNACE FOR HEAT TREATMENT OF SMALL ARTICLES.

flame from the burners encircles the inside walls of the chamber. There is no direct flame contact with the heated parts and the atmosphere can be made a reducing one, so that the articles are not oxidized or decarburized. The gas and air supplies are regulable, hand operated valve provided with pointers and scales.

The furnace door is counterbalanced for ease in movement and a hinged mica screen is provided which obviates the use of coloured glasses by the operator.

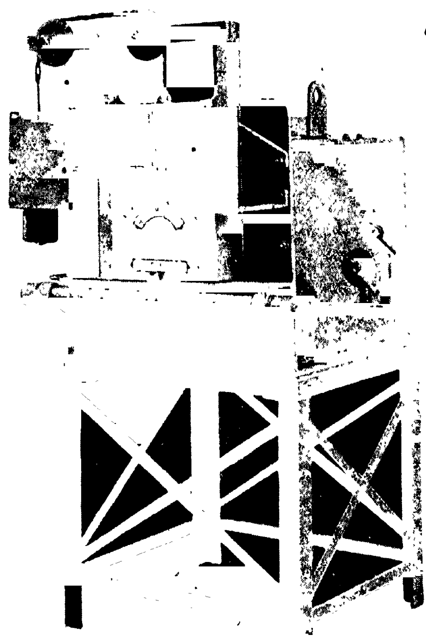


FIG. 227.—GAS-AND-AIR BLAST FURNACE.

Temperatures up to about 1300° C. can be obtained with this type of furnace, but the normal hardening temperatures seldom exceed about 900° C.

The sizes of the chambers or ovens vary from 9 inches to 14 inches wide by 5 inches in height.

Fig. 228 illustrates a gas-heated furnace suitable for forgings of irregular shape, for heating up blanks and parts for drop

forgings. The furnace door may be left open the whole time if required. The air blast used works at about 1 pound per square inch pressure, and both gas and air supplies can be regulated. The dimensions of this furnace measure 30 inches deep × 24 inches wide × 12 inches in height, the door opening being 24 inches wide × 7 inches high.

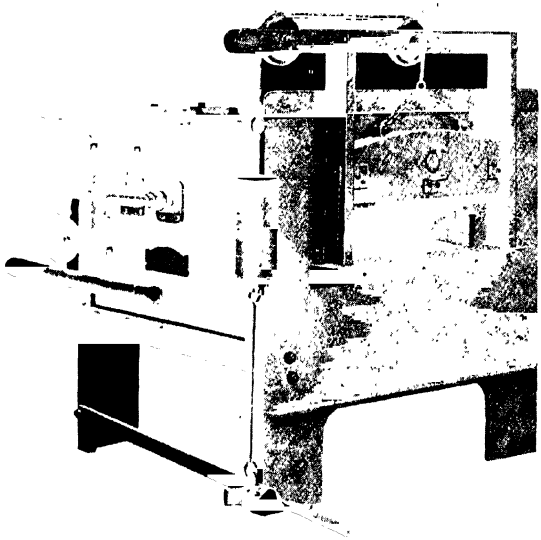


FIG. 228.—RICHMOND FORGING FURNACE.

Tempering Furnaces.

The use of gas for heating up lead and salt baths for tempering purposes is very convenient, for it enables the temperatures to be regulated with accuracy, and is clean in operation.

Fig. 229 illustrates a typical natural draught gas-heated lead tempering furnace for tempering articles such as sword-blades, cutlery, shafts, etc., in the horizontal position; in another design articles may be tempered in the vertical posi-

tion. In the type illustrated, the heating gas fumes and those from the lead bath are led away through the chimneys shown.

Fig. 230 illustrates a long type of natural draught gas-heated regenerator lead bath furnace for annealing aeroplane stream-

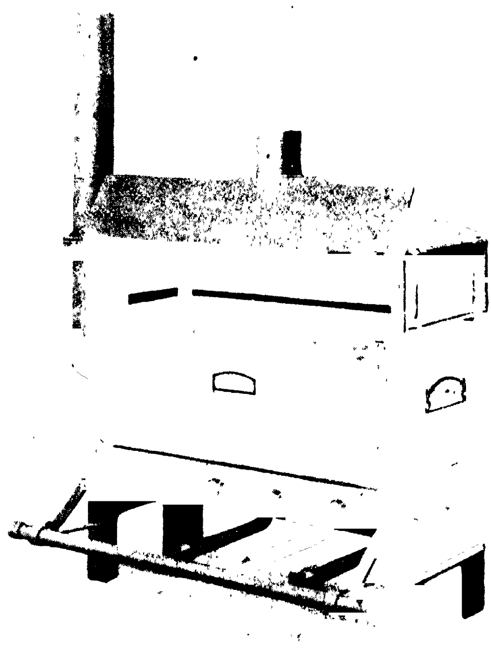


FIG. 229.—RICHMOND NATURAL DRAUGHT GAS-HEATED LEAD TEMPERING BATH.

line wires, rods, and tubes, etc. The burners and flues are so arranged that the flame is drawn from the top of the furnace down to the bottom of the lead trough, and thence to the flues on the other side of the furnace to avoid the cutting action of the flame on the bottom of the trough.

Oil-Fired Furnaces.

In cases where it is not possible or convenient to use gas for heating the furnace, any of the crude oils may be employed, such as petroleum, tar products, and other heavy oils; alternatively lighter oils or mixtures of lighter oils and gas tar can be used.

The calorific values of most of the oils employed for heating purposes are given in Table CXXXV. and in comparison with coal and coke it will be seen that they give a higher heating value for the same weight and volume.

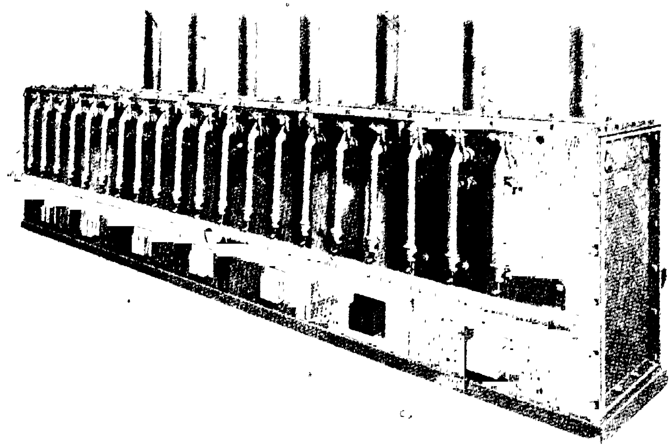


FIG. 230.—LEAD ANNEALING BATH FOR STREAMLINE WIRES, TUBES, ETC.

Fuel oils are, moreover, more convenient to store and to use, clean in action, and the heating is capable of easy regulation.

There are four common systems in use for burning oil fuel—namely, (*a*) gravity feed; (*b*) column gravity feed; (*c*) pneumatic feed, and (*d*) oil pump feed.

The tar obtained from by-product coke ovens is frequently employed as a fuel, and the " water-gas tar " from gas works

is also an excellent fuel; it has a calorific value of about 17,000 B.T.U.'s per pound, which is equivalent to about 162,000 B.T.U.'s per gallon. The quantity of oil equivalent to 1 ton of coal in good drop-forging practice is about 60 gallons, and it is convenient to note that six gallons of crude Texas oil are equivalent to 1000 cubic feet of natural gas.

When using oil fuel in furnaces it is necessary to atomize the oil with steam or air under pressure, the pressures employed varying from about 20 to 80 pounds per square inch according as the fuel is light or heavy, and varying to some

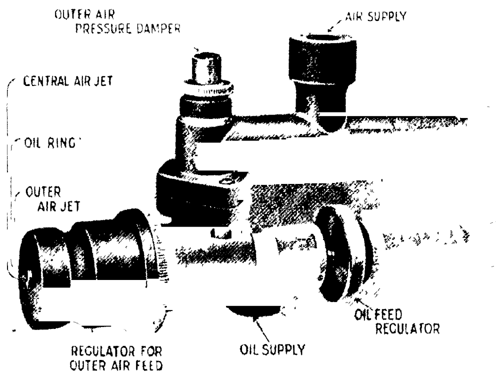


FIG. 231.—DAVIS TWIN JET OIL ATOMISER.

extent with the size of furnace; for large furnaces the greater atomization or "spread" necessitates the use of the higher pressures. The amount of the air required for combustion which is actually used for atomizing the fuel is about 2 to 4 per cent. of the whole, and it should be the aim of the oil furnace designer to keep down the amount of atomizing air to the minimum. The remaining bulk of the air for combustion is admitted under a low pressure, of from 2 to 5 ounces per square inch.

Fig. 231 illustrates the Davis twin-jet atomizer fuel oil burner for furnace work in which the oil is efficiently atomized.

It will be seen from the illustration that there is an inner and an outer air jet, with an annular oil jet in between. Each is capable of independent regulation. These burners are primarily intended for heavy oils, such as petroleum, tar oils, and similar oils, and air pressures of 20 pounds per square inch, or steam pressure of 40 pounds per square inch, and above should be employed.

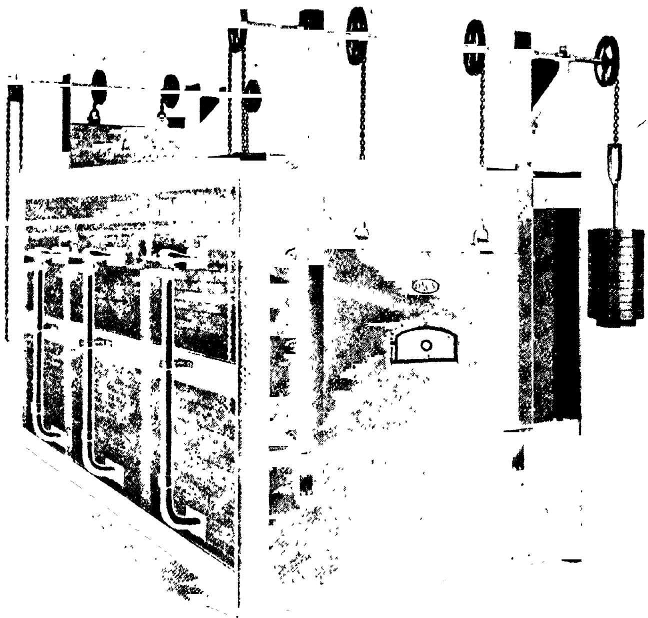


FIG. 232.—DAVIS TWIN JET OIL-FIRED FURNACE.

The range of oil consumptions in the smallest type of this burner varies from ½ to 4 gallons per hour, the sizes of the oil and air supply pipes being ¼ inch and ½ inch gas barrel respectively.

In the larger type the oil consumption can be varied from 8 to 25 gallons per hour, the oil and air pipes being ¾ inch and 1¾ inches gas, respectively.

Fig. 232 shows the application of the above oil-firing principle to an oven for heating steel parts, such as irregular forgings, billets, and similar objects; the oven shown is of the over-fired down draught type working on a semi-reverberatory principle to ensure efficient and uniform heating, for there is a downward displacement of the gases through a main flue situated beneath the floor of the oven. A short uptake only is required with this type of oven.

The air used for pulverizing the oil is heated by the escaping gases in the main flue, and in this manner the efficiency of the whole system is high; indeed, as compared with the use of coal a considerable increase in efficiency is shown.

With the type of furnace illustrated working temperatures up to 1350° C. can be attained.

Coke-Fired Furnaces.

The use of coke is very convenient in cases of isolated factories away from gas supplies, and efficient coke furnaces are now available for all of the heat treatment processes occurring in automobile and aircraft work.

Fig. 233 shows a small type of "Richmond" natural draught self-contained coke-fired furnace suitable for annealing, hardening, case-hardening, reheating, and similar operations. The furnace illustrated is termed the "in-flame" type of coke-fired furnace, in which the heated gases are directed from either side (as shown in the cross-section view) and are carried off by the flue and funnel at the front or opposite end of the furnace, in such a manner that the whole of the furnace bed and chamber is uniformly heated.

The sizes of the furnaces vary from: length A = 30 inches, width B = 12 inches, width C = 9 inches, up to A = 60 inches, B = 36 inches, C = 21 inches in eight sizes.

Figs. 234 and 235 illustrate the construction of the larger coal-fired regenerator muffle and oven furnaces which are suitable for operations, such as annealing, normalizing, hardening, case-hardening, plate and billet heating, steel frame bend-

ing, melting metals, enamelling, glass annealing, firing of pottery and similar processes.

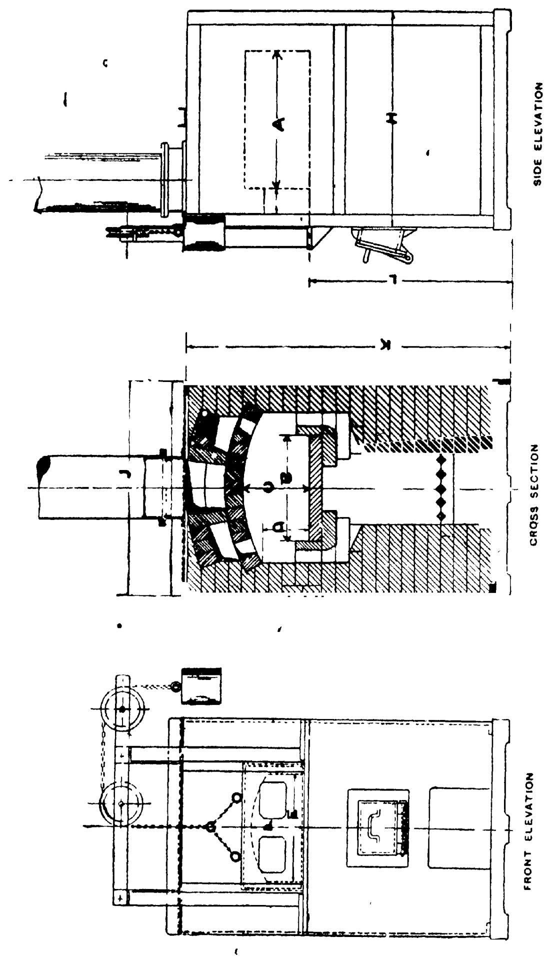
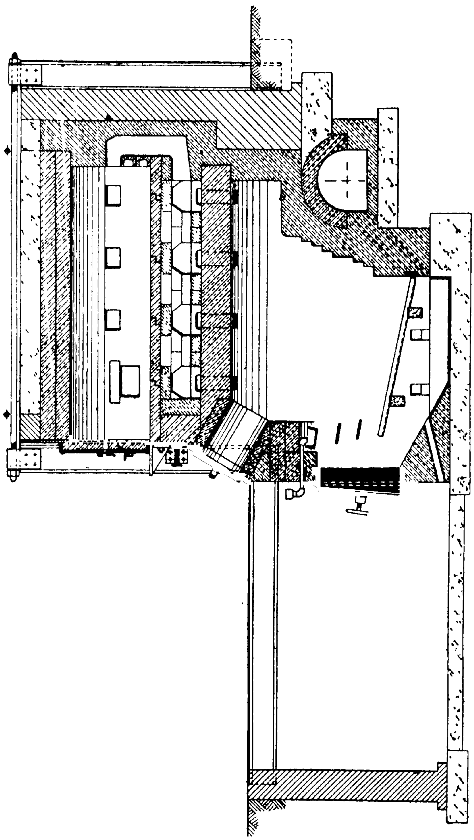


FIG. 233.—RICHMOND SMALL TYPE COKE FURNACE.

These furnaces are usually worked in batteries of two or four. They are provided with dampers so that the heats of the furnace can be efficiently controlled, and the whole of the regenerator

flues are always in view; these flues are so designed that any dust falls to the bottom, where it can be easily cleared away, and no choking of the flues can occur.



Longitudinal Section of Oven Furnace

FIG. 234.—RICHMOND LARGE COKE-FIRED OVEN

The formation of the panels of the regenerator tiles greatly increases the conductivity, and at the same time a larger area of heating surface is presented to the gas and air. The construction of the flue beds and cross-joints is so designed that in the event of a tile breaking, short-circuiting of the gases is impossible.

Automatic Electric Hardening Furnace.

An ingenious and accurate method of hardening steels is embodied in the Wild-Barfield hardening apparatus, which is shown illustrated in Fig. 236.

The principle of the method used depends upon the fact that at the critical or Ar. 2 point (which is the proper temperature for hardening) the metal becomes non-magnetic. A gal-

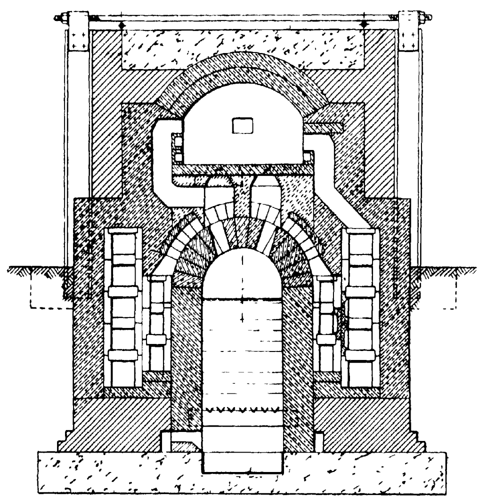


FIG. 235.—RICHMOND LARGE COKE-FIRED OVEN.

vanometer is provided for immediately notifying the operator that the correct quenching temperature has been attained.

Referring to Fig. 236, the inner pot *A* is the furnace chamber, and contains a special mixture of salts having a comparatively low melting, but a high vaporizing, point. The pot *A* is wound with a heating coil *B*, and between this coil and the outside of the furnace *D* is a special non-conducting lagging *C*. The ends of the outside insulated copper windings *E* are connected to a special galvanometer.

When a current of electricity is passed through *B* it quickly

heats the furnace and renders the salt molten. The winding *B* also magnetizes any steel article that is placed in the furnace. Immediately the critical temperature is attained the steel loses its magnetism and the galvanometer indicator at once notifies the fact; the articles are then at the correct temperature for quenching.

This method has the advantages of being clean, and gives uniform heating and certainty of the correct hardening temperature.

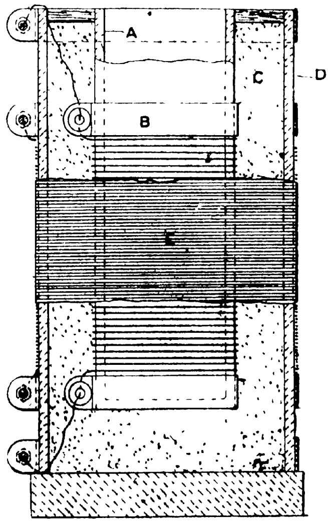


FIG. 236.—THE WILD-BARFIELD AUTOMATIC HARDENING FURNACE.

Furnaces for Melting Non-Ferrous Metals, etc.

The crucible types of furnace are considered to be more efficient and more convenient to use for melting purposes, and the oil-gas and electric methods of heating are preferable for most industrial and works processes over the coal and coke ones.

The furnaces employed may be of the fixed "ladling" type, or of the "tilting" type.

Fig. 237 illustrates the principle of the Monometer tilting

type furnace, suitable for melting steel, copper, brass, gun-metal, aluminium and other metals, and adaptable either for gas or oil heating. An outside view of this furnace is shown in Fig. 238.

The combustion chamber is in the form of an annular chamber, concentric with but situated below the crucible, and it is connected to the melting chamber by means of suitably inclined ducts or passages; this form of combustion chamber,

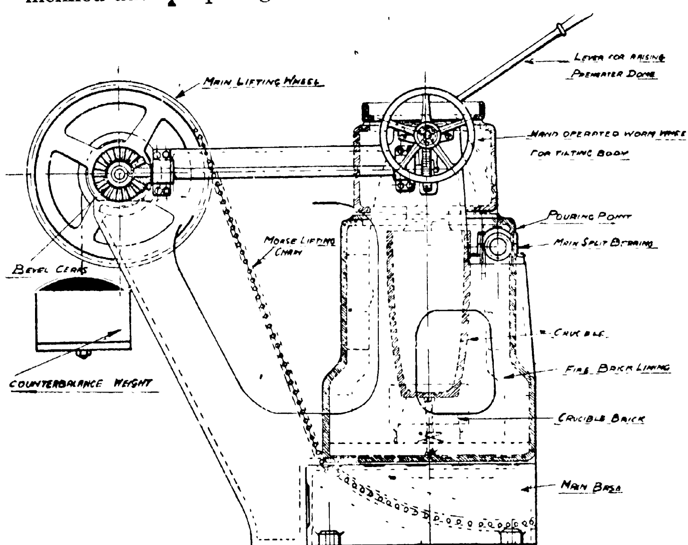


FIG. 237.—THE MONOMETER TILTING FURNACE.

by delaying the escape of the products of combustion, produces an uniform and evenly distributed heating of the crucible.

The method of tilting the crucible and its contents for pouring will be readily followed from the diagrams; it will be seen that there is a grooved portion on the bottom of the furnace body which engages with the Morse lifting chain which passes over a large chain-wheel on the balance weight shaft. A hand-operated wheel is provided for tilting the crucible, through

the medium of a worm and worm-wheel and a pair of bevel wheels; a reduction gearing is embodied in this mechanism so that only a small effort is required to tilt the furnace.

The axis about which the furnace body is rotated in the pouring process is in alignment with the pouring lip. The construction of the furnace is such that it is self-contained,

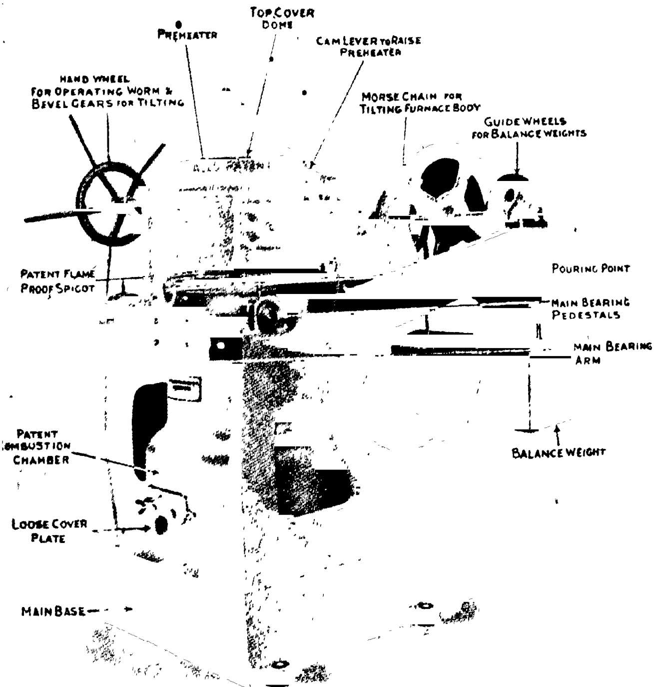


FIG. 238.—MONOMETER TILTING FURNACE.

and as the oil burner directs the oil tangentially into the combustion chamber and is attached to the furnace body so as to move with it, the firing operation can be continued during the actual pouring process.

The melting itself is carried out in a non-oxidizable or reducing atmosphere.

When gas* is used for heating, a special form of automatic heat-regulating device or thermostat is employed, by which the temperatures can be maintained within about 5° F. of the correct values.

Fig. 239 illustrates this type of heat regulator, which is mechanical in its action. By means of the adjusting screw shown at the top the temperature can be varied from 100° F. up to 2000° F. The rod indicated on the left-hand side rests in the molten metal, oven, or furnace bed, and the gas-regulating device is thermally operated therefrom. The gas (or oil) is started at

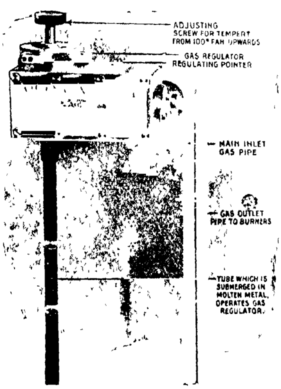


FIG 239.—MONOMETER GAS REGULATOR.

full pressure until the desired temperature is reached, when the automatic regulator cuts off the supply until only the minimum amount of gas (or oil) necessary to maintain the temperature is burning; any cooling of the furnace or melted metal causes the regulating device to turn on more gas (or oil) until the temperature is restored. In this way not only is a uniform temperature obtained but a marked economy in fuel is effected.

Figs. 240 and 241 show a Wright-Morgan forced-draught coke-fired furnace of the tilting type for melting non-ferrous metals, but suitable in certain smaller sizes for iron and steel.

* The same device can also be used for oil firing.

The crucibles taken by these furnaces vary from 200 to 1000 pounds capacity for brass, aluminium, and copper alloys.

The furnaces are all fitted with a swing-back preheater, which covers the top of the furnace body with a loose internal muffle ring and cover resting on the crucible when melting is in progress and which keeps the metal in the crucible free from contact with the combustion products, as shown in Fig. 240;

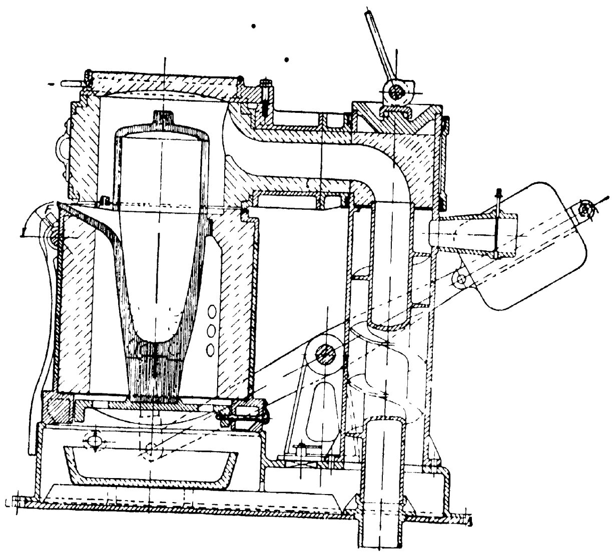


FIG. 240.—THE WRIGHT MORGAN COKE-FIRED TILTING FURNACE.

in this manner the loss in melting is considerably reduced. The furnace shown has a regenerative flue which carries all of the fumes out of the building into a main chimney.

For melting copper alloys an air pressure of $1\frac{1}{2}$ to 2 inches of water is required and it is usual to supply electric fans for this purpose. A natural draught inlet is also provided so that it can be used in place of the fan.

The furnaces are made in two sections—namely, the body section, which tilts on an axis in line with the lip of the crucible, and a preheater section fitted with solid cover and flue outlet to the downtake regenerator pipe at the rear.

The incoming air is heated in this regenerator to 250° to 300° C., and then passes into the furnace, partly through the grate bars, the annular space above the grate bars and the side air-holes in the firebrick linings. In this manner the air-jets entering through the bars are met at right angles by the annular flow of air over the top bars. Fresh air is introduced to the fuel above the stand level by means of the side holes through the furnace lining; excessive cutting of the crucible base is thus

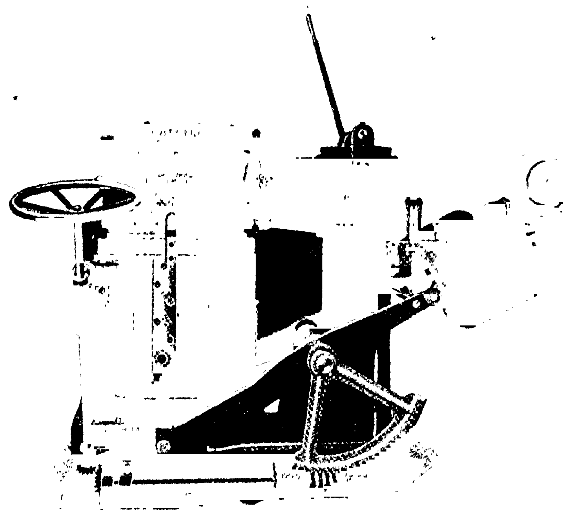


FIG. 241.—WRIGHT-MORGAN FORCE-DRAUGHT COKE-FIRED TILTING FURNACE.

prevented. All fumes are exhausted through an underground flue to a main chimney, for which, as the furnace works under a forced draught, only a small stack is required.

Soft Metal Melting Furnace.

Furnaces intended for melting lead, tin, white metal and soft metals in general, do not, of course, require to be worked at appreciably high temperatures (about 600° C. as a maximum), but it is essential that means shall be provided to prevent

surface oxidation, over-heating, and homogeneous mixing of the metal.

Fig. 242 illustrates the Monometer soft metal melting furnace which has been designed to fulfil the above require-

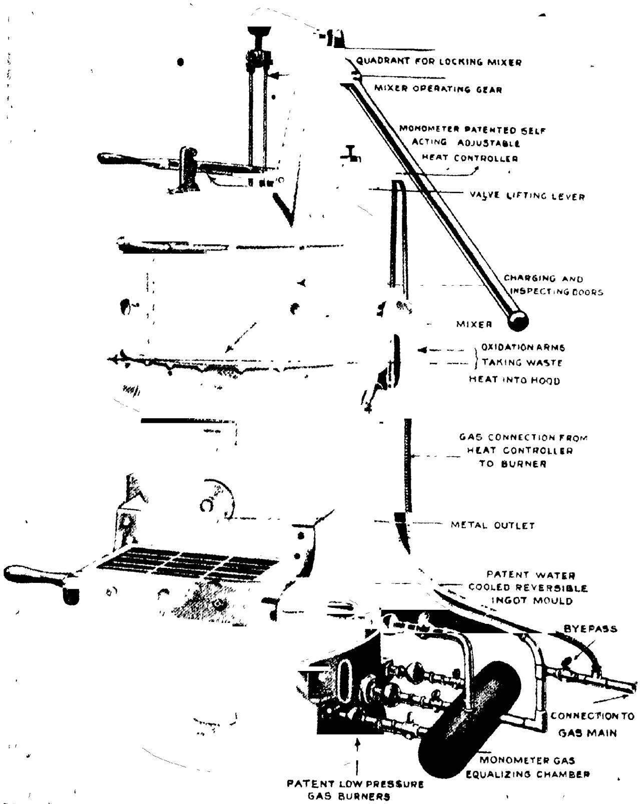


FIG. 242.—MONOMETER SOFT METAL MELTING FURNACE

ments. In this type the melting pot is enclosed, the inert gases being brought into the chamber above it. An automatic gas regulator* is provided to prevent overheating, and a special

* See p. 548.

mixing appliance is fitted. This mixer is in the form of rotating paddles attached to a vertical hollow spindle or sleeve, which are revolved in the melting pot by means of external arms, the weight of the metal being taken on a ball bearing Passing down the centre of the mixer sleeve is a valve stem. The valve which is at the bottom of the melting pot is cone-seated and is operated by means of a hand wheel at the top of the furnace; in this way the metal can be tapped from the bottom of the pot, where it is purest and free from dross.

The furnace can also be fitted with oil-fuel heaters with self regulators.

Fuel Consumptions and Outputs.

Some interesting figures are given by the Monometer Company for the fuel consumptions and other particulars of their melting furnaces when using oil and gas. These are shown in the following table:

TABLE CXXXVII.

FUEL CONSUMPTIONS, COSTS, AND OUTPUTS OF MELTING FURNACES.

Metal Melted.	*Fuel Used.*	*Crucible Capacity in Pounds.*	*12 Hours' Output in Pounds.*	*Cost in Shillings.*	*Consumption of Metal per Cwt.*
Copper	oil	800	5000	80s. per ton	1¼ gallons
	gas	800	3000	3s. per 1000 cubic feet	450 cubic feet
Cupro-nickel	oil	800	3000	80s. per ton	2 gallons
	gas	800	2200	3s. per 1000 cubic feet	820 cubic feet
Cartridge metal	oil	800	6000	80s. per ton	1 gallon
	gas	800	4000	3s. per 1000 cubic feet	335 cubic feet

Metal Melted.	*Fuel Used.*	*Price per Cwt. of Metal of Fuel.*	*Life of Crucible in Melts.*	*Cost of Crucible per Cwt. of Metal.*	*Life of Lining in Months.*
Copper	oil	5½d.	40 (min.)	4s. 6d.	3½
	gas	16s. 2d.	30	6d.	3
Cupro-nickel	oil	8s. 4d.	24	7s. 6d.	2½ (min.)
	gas	29s. 5d.	16	11s. 3d.	1 to 2 (min.)
Cartridge metal	oil	4s. 2d.	66 (min.)	2¾d.	5 (aver.)
	gas	1s. 0d.	50	3s. 6d.	3 to 4 (aver.)

The following particulars refer to results obtained with a Richmond gas-and-air blast heated crucible furnace:

	Cubic Feet.	*B.T.U.'s*
(A) *Copper.* Poured at 1200° C.		
Average coal gas consumption per pound for 5 melts.	3·70	1924
Average coal gas consumption per pound for 6 melts.	3·50	1820
Average coal gas consumption per pound for 7 melts.	3·35	1742
(B) *Brass.* Poured at 1000° C.		
Average gas consumption per pound of metal for 6 melts.	2·25	1203
Average gas consumption per pound of metal for 12 melts.	1·92	1031
Average gas consumption per pound of metal for 15 melts.	1·86	996

The effect of preheating the air and the metal with the furnace products leads to a considerable saving in fuel, as the following typical results for melting yellow brass show:

	Gas Consumption per Pound of Metal Melted.	
Number of consecutive melts	4	6
	Cubic Feet.	*Cubic Feet.*
Consumption with no preheater	3·10	2·91
Consumption with brass only preheated ..	2·72	2·48
Consumption with brass and air preheated ..	2·42	2·17

The following results of an average week's working with a 100 pound electric bronze melting furnace are also of interest:

Nature of charge	Electric bronze (ingots and scrap).
Nature of work	Sand castings.
Gas consumption (per 100 pound melt)	300 cubic feet.
Number of heats per 8 hour shift	11.
Average time per melt	42 minutes.
Life of crucible	34 melts per pot.

CHAPTER X

PYROMETRY

Pyrometry.

From what has already been mentioned in connexion with the subject of the heat treatment of metals, the importance of correct temperature regulation and measurement will need no further emphasis; it may, however, be remarked, that in practically all industrial processes, such as the melting and heat treatment of metals, galvanizing, rust-proofing, enamelling, and other thermal processes, suitable thermometers or pyrometers are now available in commercial form and are invariably employed.

Not only is the uniformity of output maintained, and the percentage of rejections minimized, but the output itself is often greatly improved by utilizing accurate thermometric methods.

The subject of industrial pyrometry is too wide to be dealt with here in any but a brief form, so that attention will be merely confined to pointing out the principal methods employed, and to illustrating these methods with typical examples. For fuller particulars the reader is referred to the special works upon the subject, some of which are given in the footnotes.*

* *Vide* (*a*) "Industrial Pyrometry," by C. R. Darling, Cantor Lectures, 1911, Royal Society of Arts.

(*b*) "Recent Progress in Pyrometry," by C. R. Darling, Royal Society of Arts, May, 1915.

(*c*) Chapter on "Pyrometry" in "An Introduction to Metallurgy," by Sir W. C. Roberts-Austen (Griffin and Co., Ltd.).

(*d*) The Cambridge Scientific Instrument Co.'s Industrial Thermometer Publications.

(*e*) "The Measurement of Extreme Temperatures," by H. L. Callendar, Proc. Roy. Inst., vol. xvi., p. 97.

(*f*) "Practical Pyrometry," by R. S. Whipple, *Engineering Review*, vol. xvii., p. 148.

(*g*) "Modern Methods of Pyrometry," by C. W. Waidner, Proc. Eng. Soc. of Western Pennsylvania, vol. xx., p. 1313.

Temperatures to be Measured.

The temperatures occurring in most industrial processes range from atmospheric up to those of the melting points of the metals, the temperatures for the common metals varying from 200° to 1600° C.

Table CXXXVIII. shows some of the more important temperatures involved in practical metal smelting and processes.

TABLE CXXXVIII.

MELTING POINTS OF METALS AND OTHER COMMON MATERIALS.

METALS AND ALLOYS.

° C.		° C.	
3500 to 4000	Carbon.	1435	Steel (1·0 per cent. C).
3000	Tungsten.	1400	Steel (1·5 per cent. C).
2910	Tantulum.	1350	Steel (2·0 per cent. C).
2700	Osmium.	1345	Manganese steel (13 per cent. Mn).
2450	Molybdenum.	1330	Ferro-titanium (25 per cent. Ti).
2300	Zirconium.	1230	Ferro-nickel (25 per cent. Ni).
2290	Iridium.	1225	Manganese.
2000 to 2500	Boron.	1210	Ferro-manganese (80 per cent. Mn).
1900 (?)	Ruthenium.	1100	Cast iron (average).
1800	Titanium.	1083	Copper.
1720	Vanadium.	1063	Gold.
1700 to 1790	Platinum.	961	Silver
1690	Thorium.	658	Aluminium.
1550	Palladium.	631	Antimony.
1510	Chromium.	419	Zinc.
1505	Pure iron.	327	Lead.
1490	Cobalt.	232	Tin.
1475	Steel (0·5 per cent. C).		
1450	Nickel.		

REFRACTORY AND OTHER MATERIALS, ETC.

° C.		° C.	
2400	Lime and magnesia.	1400	Inferior firebricks melt.
2180	Chromite.	1350	Copper slag.
2165	Magnesia brick.	1318	Tin slag.
2050	Chromite brick.	954	Litharge.
2010	Pure alumina.	780	Calcium.
1820	Bauxite.	633	Magnesium.
1800	Best firebricks.	620	Cerium.
1800	Bauxite clay.	115 to 120	Sulphur.
1750	Pure silica.	100	Boiling water.
1700 to 1705	Silica brick.	97	Sodium.
1565 to 1785	Bauxite brick.	68	White beeswax.
1550	Silica softens; inferior firebricks soften.	61	Yellow beeswax.
1430	Puddle slag.	44	Phosphorus.
1420	Silicon.	- 39	Mercury.
		- 182	Liquid air.
		- 273	Absolute zero.

Temperature Standards and Fixed Points.

Before proceeding to the description of a few typical temperature measurement devices, mention will here be made of some of the better known "fixed" points, which are used for reference chiefly in pyrometry.

The "fixed points" mentioned are the accurately known melting or boiling points of certain solids and liquids, which are used for calibration or standardization purposes. It is a fairly simple matter to check the accuracy of any pyrometer by observing its reading at one or more of the fixed temperatures within its range.

The values given in Table CXL. refer to the pure materials; considerable errors are, however, possible unless the substances used are of a high grade of purity.

All important pyrometers may alternatively be checked or calibrated at any of the well-known testing institutions, such as the National Physical Laboratory, Teddington, or the American States Bureau of Standards.

The following table is useful in showing, approximately, the equivalent temperatures to different colours, in the case of heated iron and steel as seen in a dark room:

TABLE CXXXIX.

TEMPERATURE AND COLOUR VALUES FOR HEATED STEEL.

Colour.	*Temperature.*	
	Cent.	*Fahr.*
White (not welding heat)	1240	2264
High yellow	1130	2065
Yellow	1081	1976
Low yellow	971	1780
Bright red	923	1693
Light red	850	1561
Medium red	795	1462
Full cherry red	700	1291
Blood red	667	1231
Dull red	625	1156
Red, just visible	525	976
Black	475	886

TABLE CXL.

STANDARD TEMPERATURES OR "FIXED POINTS."*

Substance.	*Physical Condition.*	*Temperature ° C.*	*Temperature ° F.*
Water	At boiling point	100	212
Aniline	,, ,,	184	363
Naphthalene	,, ,,	218	426
Tin	At melting point	232	450
Cadmium	,, ,,	321	610
Lead	,, ,,	327	620
Zinc	,, ,,	419	786
Sulphur	At boiling point	445	832
Antimony	At melting point	631	1168
Common salt	,, ,,	800	1472
Silver (in reducing atmosphere)	,, ,,	961	1762
Gold	,, ,,	1063	1946
Copper (graphite covered)	,, ,,	1083	1982
Lithium-metasilicate ..	,, ,,	1202	2194
Nickel	,, ,,	1450	2642
Palladium	,, ,,	1550	2822
Platinum	,, ,,	1755	3190
Tungsten	,, ,,	3000 (about)	5432
Carbon arc	,, ,,	3500 (about)	6332

TABLE CXLI.

ADDITIONAL FIXED POINTS. (Dr. Northrup.)

Substance.	*Physical Condition.*	*Temperature ° C.*
Ice	Melting point	0
Benzophenon	Boiling point	305·4
Copper (in CO)	Melting point	1082·6
Diopside	,, ,,	1391·2
Cobalt	,, ,,	1489·8

Methods of Temperature Measurement.

The methods adopted for measuring temperatures are all based upon some physical property of a solid, liquid, or gas, which changes with temperature, and it is the physical effects

* From "Recent Progress in Pyrometry," by C. R. Darling, *Journ. Soc. of Arts*, May 14, 1915.

which are observed or measured, and from which the temperatures are deduced.

The following are some of the typical methods upon which temperature measurement devices are based:

(*a*) Measurement of the expansion of solids, liquids, or gases.
(*b*) Measurement of the vapour tension of vapours.
(*c*) Fusion effects of known substances.
(*d*) Ebullition or boiling effects.
(*e*) Specific heat effects (calorimetry methods).
(*f*) Heat radiation methods.
(*g*) Thermo-electrical measurements.
(*h*) Electrical resistance measurements.
(*i*) Optical methods.

There are, of course, many other methods available, based upon other physical properties such as those of viscosity, acoustics, and magnetism.

The five principal methods with which the present considerations are concerned are as follows—namely:

1. Fusion effects of solids, metals, and alloys.
2. Expansion effects of solids and liquids.
3. Radiation methods.
4. Thermo-electric methods.
5. Electrical resistance methods.

Each of these methods is applicable to certain purposes, and in many cases several alternative methods may be employed for the same purpose; this remark applies more particularly to the last three methods named.

Table CXLII. shows the temperature ranges and typical applications of the five methods above mentioned; each of these will be briefly considered in detail later.

Fusion Pyrometers.

A simple method for obtaining approximate furnace temperatures and one which is frequently employed in works practice, is to insert a number of salts, clays, or alloys of known

TABLE CXLII.

Types of Thermometers and Pyrometers, for Industrial Use.

Type.	*Principle.*	*Examples.*	*Temperature Range (Centigrade).*
Fusion	Based upon the fact that definite solids and compounds melt at a certain temperature	Seger's cones Sentinel pyrometers Various clays, alloys, and salts	0° to 2000° C.
Expansion effects	Based upon the change in length or volume of solids, liquids, and gases, on heating and cooling	Gas thermometer Mercury, Jena glass, and nitrogen Ordinary alcohol thermometer Sodium-potassium alloy and boro-silicate glass Unequal expansion of rods Contraction of porcelain	0 to 1000° C. - 40 to 500° C. - 200 to 100° C. Up to 600° C. 0 to 500° C. 0 to 1800° C.
Radiation	Depend upon the measurement of heat radiated by hot bodies	Féry's radiation pyrometer Foster's fixed focus pyrometer Wanner optical pyrometer Holborn - Kurlbaum pyrometer Siemen's pyrometer Cambridge optical pyrometer	Can be arranged for any temperature up to 5000° C. and above. Usual ranges, 500° to 1800° C. for metal processes
Thermo-electric	Based upon the measurement of the electric current or E.M.F. developed by the difference in temperature of two similar thermo-electric junctions opposed to one another	Copper-constantan Iron-constantan Iron - nickel and iron-nickel alloy of different composition Nickel-chromium and a nickel - chromium alloy of different composition Platinum-platinum iridium Two platinum-rhodium alloys	0 to 500° C. 0 to 900° C. to 1000° C. (max.) to 1200° C. (max.) to 1300° C. (max.) to 1600° C. (max.)
Electrical resistance	Based upon the increase in resistance of a metal wire when heated	Callendar platinum thermometer Siemens' resistance pyrometer Whipple's indicator* Harris's indicator*	0 to 1200° C.

* For use with resistance thermometers.

progressive melting points in the furnace and to observe which have been melted. The temperature of melting furnaces at any desired locality is often tested by inserting a rod of iron, or copper, and noting whether it melts or not.

It is possible to select a number of salts and alloys of known melting points so as to form a descending temperature series.

The values given in Tables CXLIII., CXLIV., and CXLV. will afford some useful information in connexion with fusion methods.*

TABLE CXLIII.

MATERIALS FOR FUSION PYROMETERS.

Substance.	*Melting Point.*	
	° *C.*	° *F.*
Grey forge pig iron	1220	2230
Grey pig iron	1240	2264
Anhydrous magnesium sulphate	1150	2102
Cuprous sulphide	1100	2012
Anhydrous potassium sulphate	1070	1958
Copper-zinc alloy, 95 Cu, 5 Zn	1070	1958
Potassium sulphate	1015	1860
Copper-zinc alloy, 90 Cu, 10 Zn	1055	1931
Copper-zinc alloy, 85 Cu, 15 Zn	1025	1826
Copper-zinc alloy, 80 Cu, 10 Zn	1000	1832
Sodium plumbate	1000	1832
Copper-zinc alloy, 75 Cu, 25 Zn	980	1796
Potassium bichromate	975	1788
Sodium phosphate	957	1755
Copper-zinc alloy, 70 Cu, 30 Zn	940	1725
Copper-zinc alloy, 65 Cu, 35 Zn	915	1679
Anhydrous sodium sulphate	900	1652
Copper-zinc alloy, 60 Cu, 40 Zn	890	1634
Anhydrous sodium carbonate	850	1562
Chloride of tin ($SnCl_2$)	840	1544
Sodium carbonate	810	1490
Common salt	800	1472

It is usual to insert a number of salts of progressively increasing melting points in the furnace; then if, for example, a salt such as potassium chloride was just melted, and the next salt, calcium chloride, was not melted, the temperature (see Table CXLV.) would lie between 740° and 755° C.

Seger's cones are another example of the use of this method, in which a number of clays of various compositions and with

* Also see Table CXLVI.

TABLE CXLIV.

Melting Points of Low Fusion Point Alloys.

Composition per Cent.				*Melting Point. ° F.*	*Composition per Cent.*			*Melting Point. ° F.*
Bismuth.	*Lead.*	*Tin.*	*Cadmium.*		*Bismuth.*	*Lead.*	*Tin.*	
50·0	25·0	12·5	12·5	149	20·0	40·0	40·0	293
50·1	26·6	13·3	10·0	158	19·0	38·0	43·0	298
38·4	30·8	15·4	15·4	160	18·1	36·2	45·7	304
27·5	27·5	10·5	34·5	167	17·3	34·6	48·1	311
50·0	34·5	9·3	6·2	171	16·6	33·2	50·2	316
—	25·0	50·0	25·0	187	16·0	36·0	48·0	311
50·0	31·2	18·0	—	201	15·3	38·8	45·9	309
55·6	—	33·3	11·1	203	14·8	40·2	45·0	307
50·0	—	25·0	25·0	203	14·0	43·0	43·0	309
47·0	35·5	17·5	—	208	13·7	44·8	41·5	320
42·1	42·1	15·8	—	226	13·3	46·6	40·1	329
40·0	40·0	20·0	—	235	12·8	49·0	38·2	342
36·5	36·5	27·0	—	243	12·5	50·0	37·5	352
33·3	33·4	33·3	—	253	11·7	46·8	41·5	333
30·8	38·4	30·8	—	266	11·4	45·6	43·0	329
28·5	43·0	28·5	—	270	11·2	44·4	44·4	320
25·0	50·0	25·0	—	300	10·8	43·2	46·0	318
23·5	47·0	29·5	—	304	10·5	42·0	47·5	320
22·2	44·4	33·4	—	289	10·2	41·0	48·8	322
21·0	42·0	37·0	—	289	10·0	40·0	50·0	324

TABLE CXLV.

Materials for Fusion Pyrometers.

Substance.	*Melting Point.*	
	° *C.*	° *F.*
Barium carbonate	795	1462
Sodium chloride	775	1426
Calcium chloride	755	1391
Potassium chloride	740	1364
Aluminium	657	1214
1 molecule salt + 1 molecule potassium chloride	650	1201
Barium nitrate	592	1096
Sulphur (boiling point)	445	833
Zinc	419	735
Potassium chlorate	370	698
Lead	327	620
Tin	232	450

melting points ranging from 590° C. (or 1094° F.) up to 1890° C. (or 3434° F.) are employed in the forms of vertical cones or pyramids. The temperature intervals are below 30° C. in each case.

A number of these cones of progressive melting points are inserted in the furnace, and after an interval are withdrawn. If the correct range of cones has been chosen they will be found to have the appearance shown in Fig. 243, in which

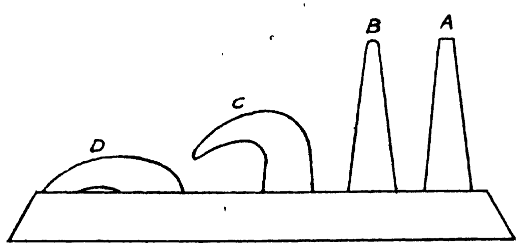


FIG. 243.—ILLUSTRATING THE PRINCIPLE OF SEGER'S CONES.

cone *D* has collapsed, *C* is bent over, and *B* is slightly rounded. The correct furnace temperature in this case corresponds to the melting point of cone *C*.

Expansion Thermometers.

Temperatures varying from considerably below zero up to about 1200° C. may be measured by means of this type of instrument. Thermometers for the highest temperatures—namely, up to 1200° C.—usually employ the principle of measuring the expansion of an iron rod encased in a fireclay tube, or of graphite in an iron tube.

For temperatures up to about 600° C., a potassium-sodium alloy is employed instead of mercury, using a hard glass tube.

For temperatures up to about 550° C. (or about 1000° F.) mercury thermometers are employed with nitrogen as the gas in the stem, and in which very hard glass, or boro-silicate glass, is employed for the bulb and the tube.

Fig. 244 shows a typical instrument* of this kind which is widely employed for ascertaining the temperatures of lead and salt baths, tinning baths, galvanizing and spelter baths, for soldering machines, etc. The section of the bore is elliptical and the space above the mercury is filled with an inert gas. The glass stem itself is protected by an inner steel sheath, the spaces between the glass, the steel sheath, and the outer tube being packed with insulating material, so that varying depths of immersion may be used without appreciable stem errors.

The bulb chamber is of cast iron and the space between the bulb and the chamber is filled with copper dust, so that the heat is quickly conducted to the bulb and rapid readings may be taken. The outer stem is nickel plated.

The scale is divided in Fahrenheit degrees from 210° to 1000°, but instruments for special ranges, and with more open scales for intermediate temperatures, are made.

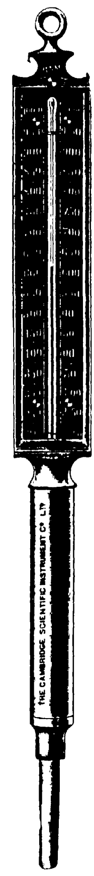


FIG. 244.—IMMERSION THERMOMETER FOR TEMPERATURES UP TO 1000° F.

A useful thermometer of this class, which is made by the same manufacturers, is one for water and oil quenching baths, with a temperature range either of 30° to 220° F. or 100° to 250° F. The higher temperature range thermometers may also be used for ascertaining tempering oven temperatures, in which case the bulb is copper plated to a depth of 1 mm., and there is no outer chamber, so that the thermometer is much more sensitive. A wire guard is supplied for protecting the bulb itself.

* Made by the Cambridge Scientific Instrument Co., Ltd.

Recording Thermometer.

Figs. 245 and 246 illustrate a useful form of self-recording mercury type of thermometer* capable of reading up to 540° C. (or 1000° F.).

The steel bulb A and capillary tube B are filled with mercury and connected up to a special form of Bourdon spiral C, which actuates, through a simple mechanism, the recording hand shown.

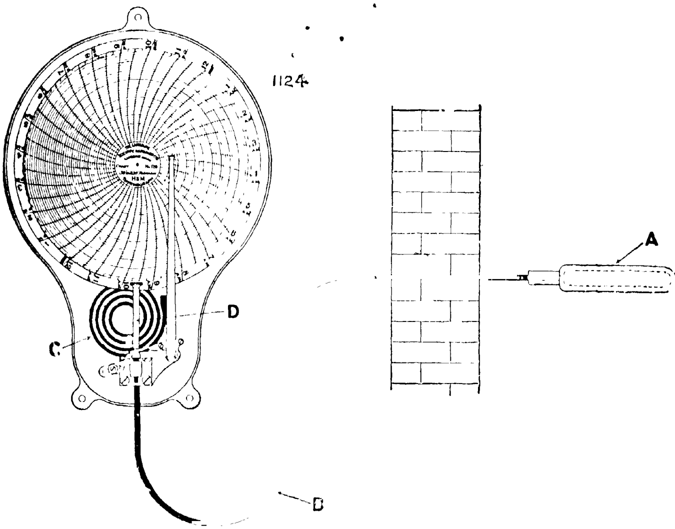


FIG. 245.—THE *H.* AND *M.* THERMOMETER.

The whole system is filled with mercury, and changes of temperatures of the bulb give rise to corresponding changes of pressure in the system, which are magnified and recorded or indicated by means of the pencil mechanism shown.

The circular charts used are $9\frac{1}{2}$ inches in diameter, and they are printed with uniform scale divisions; the chart speeds are so arranged that one complete revolution is made either in twenty-four hours or seven days.

* The *H.* and *M.* Thermometer, made by the Cambridge Scientific Instrument Co., Ltd.

Radiation and Optical Pyrometers.

The principle of the radiation pyrometer depends upon the measurement at a distance of the heat of radiation emitted by the body whose temperature it is required to measure.

It has been shown by Tyndall, Stefan, and others, that the heat energy radiated by a hot body varies as the fourth power

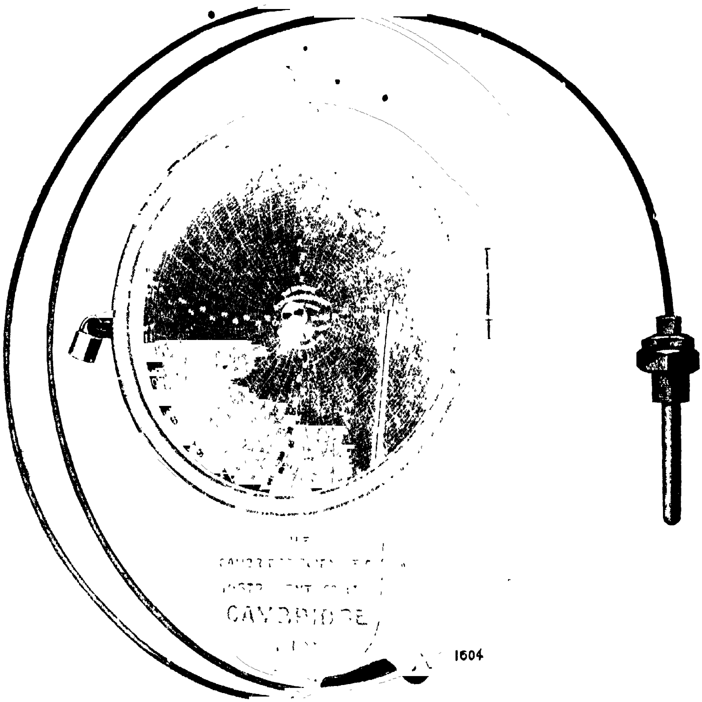


FIG. 246.—*H.* AND *M.* THERMOMETER RECORDER.

of the absolute temperature,* and that black bodies (such as those with lamp-black or sooty surfaces) are better radiators of heat than polished or bright bodies.

As the enclosures within furnaces are true black bodies in

* Absolute temperature Centigrade = t°C + 273.
,, ,, Fahrenheit = T°F + 461.

the above sense, the above law may be applied to most industrial temperatures.

This law may be expressed in the following manner:

$$\frac{R_1}{R_2} = \frac{T_1^4}{T_2^4}$$

where R_1 and R_2 are the quantities of heats radiated from bodies at absolute temperatures of T_1 and T_2 respectively.

With most radiation pyrometers it is only necessary to know the heat at any standard temperature, or to obtain a galvanometer reading proportional to this heat, in order to be able to measure any other temperature.

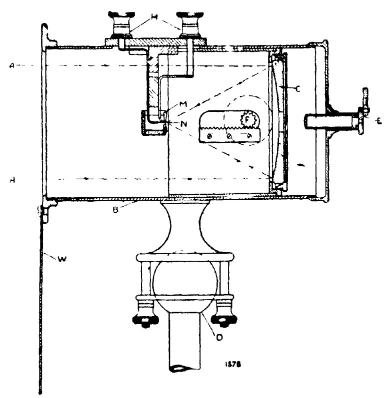


FIG. 247.—THE FÉRY RADIATION PYROMETER.

Radiation pyrometers may be employed for measuring the temperatures of any objects, and there is no real limit to the upper temperatures which can be measured; for example, the fusion points of carbon and tungsten (4000° to 3000° C.) may be readily measured, and this type of instrument possesses the advantage of being out of contact with the heated object, and can be operated at a distance, so that there is no possibility of damage arising through excessive heating.

In most instruments the heat rays are focussed upon a spiral or thermo-electric junction, and the temperature is measured or recorded electrically.

The Féry Radiation Pyrometer.

This instrument consists of a telescope, as shown in Fig. 247, in which the heat rays A from the furnace are received on the concave mirror C and brought to a focus at N. It is necessary to employ such a mirror, as a glass focussing lens would stop a large amount of the heat of radiation and the fourth power law would not apply with any accuracy. Looking through the eyepiece E, the observer sees an image of the furnace in a small mirror, M, and is able to point the telescope on the exact spot at which the temperature is required.

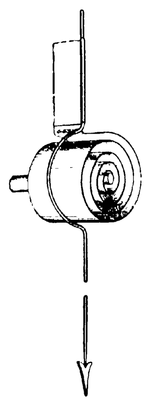


FIG. 248.

A small sensitive thermo-couple is situated just behind a small hole in the mirror M and becomes heated by the rays passing through the hole. A special device is employed for focussing the telescope whereby two semi-circular wedge-shape mirrors are fitted, and if the focus is not correct the reflected image appears to be broken by the halves of the mirrors, whereas if the focus is correct a continuous image is seen; focussing is effected by means of a knurled-headed screw attached to the pinion F.

The size of the object sighted must be at least 1 inch in

diameter for every 2 feet of distance between the telescope and the object with this particular type of instrument.

In a cheaper and less accurate form of this pyrometer, known as the "spiral type" the radiant heat is focussed upon a very small bi-metallic spiral, which controls the movement of a pointer which swings across a scale calibrated in degrees of temperature.

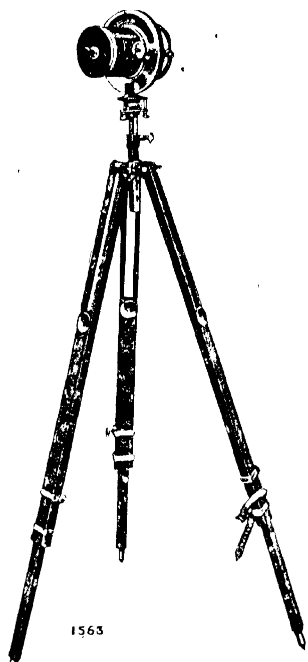


Fig. 248a.—The Féry Radiation Pyrometer and Stand.

The action of the spiral, an enlarged view of which is shown in Fig. 248, depends upon the difference of expansion in two very thin dissimilar metals soldered together flat and then wound in the form of a spiral which tends to uncoil as the temperature rises.

The latter type of instrument is self-contained, and is very

convenient for ordinary works practice. The thermo-electric type requires a galvanometer, and this may be either of the direct reading class, or may be arranged to automatically record the temperature. These three types of radiation pyro-

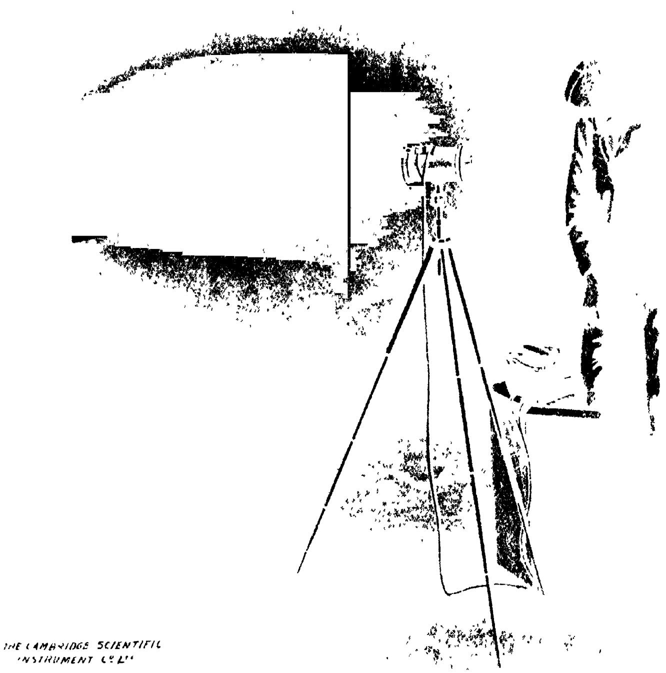


FIG. 249.—SHOWING THE OPERATION OF THE RADIATION PYROMETER.

meter—namely, the direct-reading, the self-recording, and the spiral, or portable, type are manufactured for three standard ranges—namely, from 500° to 1100° C., from 600° to 1400° C., and from 800° to 1700° C., respectively.

The Foster Fixed Focus Pyrometer.

The principal advantage of this pyrometer is that it does not require focussing; like the Féry instrument it employs a thermo-electric junction for measuring the heat of the focussed rays.

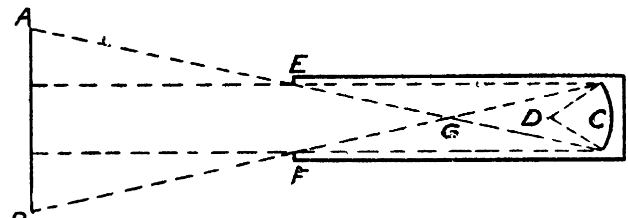


FIG. 250.—PRINCIPLE OF THE FOSTER FIXED FOCUS PYROMETER.

The principle of this instrument* is illustrated in Fig. 250, in which *C* is the focussing mirror and *D* is the thermo-couple; both are enclosed in a tube with dull black walls. The opening *EF* at the entrance to the tube is provided with sharp

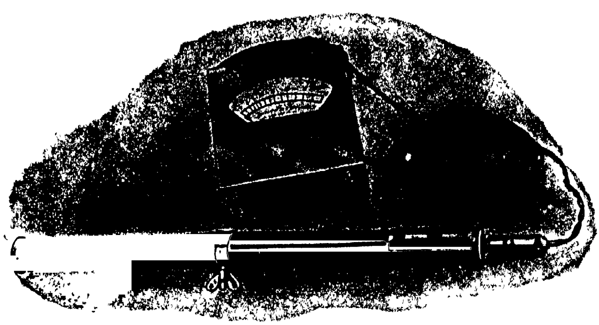


FIG. 251.—FOSTER FIXED FOCUS PYROMETER OUTFIT.

edges, and if lines be drawn so as to join the extremities of the mirror *C* with *E* and *F*, and these are produced to the hot surface *AB*, the same effect on the thermo-junction *D* will be obtained at any distance provided that the lines *GE* and *GF* when continued fall on *AB*. The instrument is so designed

* Manufactured by the Foster Instrument Co., Letchworth.

that if AB represent an object 6 inches in diameter the same reading will be obtained at any point within 5 feet of the heated body.

Fig. 251 shows the standard outfit supplied, consisting of a pyrometer, connecting leads, and galvanometer, or direct reading indicator.

These outfits are supplied for temperature ranges varying from 500° to 1000° C. (or 900° to 1800° F.) up to from 800° to 1600° C. (or 1500° to 2900° F.) in six steps.

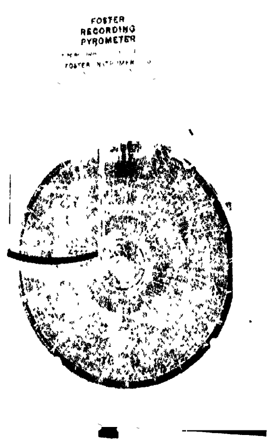


FIG. 251 A.—RECORDING PYROMETER.

The operating distance limit is fixed for each outfit; the maximum working distance should not exceed the diameter of the hot body, multiplied by a distance factor, the value of which varies for different instruments from 6 to 16.

This pyrometer is also supplied with an automatic recorder in the form of a flat circular chart, upon which an ink line is drawn, so that a time temperature record is obtained with radii as temperatures and peripheries as times.

Another form of this instrument, known as the "double

purpose outfit," shown in Fig. 252, is supplied for measuring the temperatures of molten metals, by immersing a closed fireclay or refractory tube forming one end of the instrument in the molten metal, so that it is heated to the same temperature and radiates heat to the sensitive part of the receiving

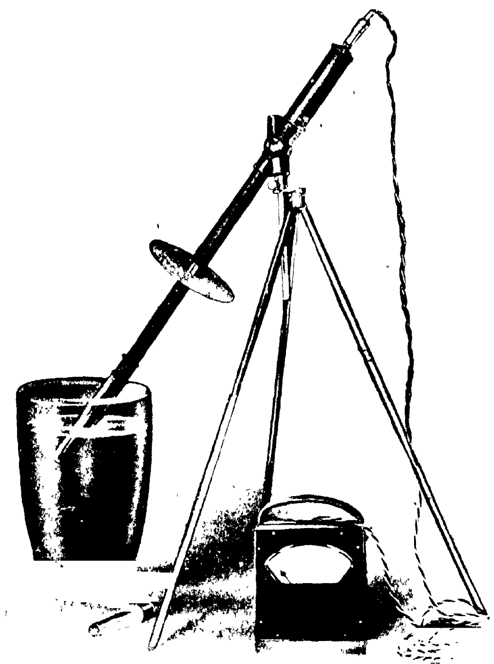


FIG. 252.—THE FOSTER DOUBLE PURPOSE PYROMETER OUTFIT.

tube, or thermo-couple telescope, situated at the other end, the temperature being either automatically recorded or read off directly.

The Cambridge Optical Pyrometer.

Some pyrometers work upon the optical principle, and employ either photometric or spectroscopic measurement devices. In

most of these instruments the method of operation consists in matching the brightness or colour of the source to be measured with that of a standard flame or light.

In the Cambridge instrument temperatures ranging from 700° to 4000° C. may be conveniently and accurately measured by unskilled operators.

The outfit as shown in Fig 253 consists of the pyrometer *A*, which includes the optical system, the electric lamp providing

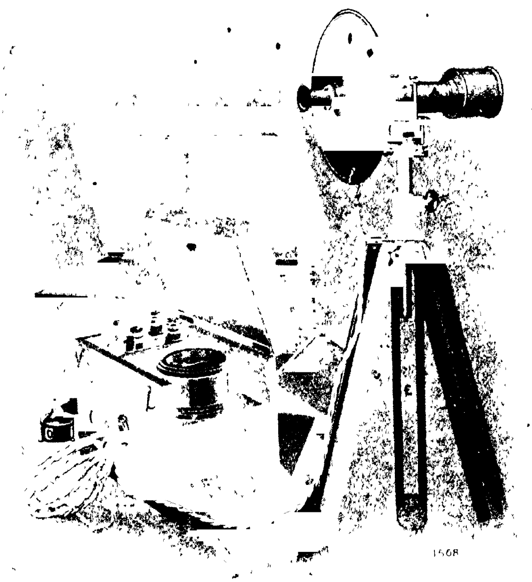


FIG. 253.—THE CAMBRIDGE OPTICAL PYROMETER OUTFIT.

the standard source of light, and the shield carrying the temperature scale and pointer, together with a 4-volt accumulator, ammeter and regulating resistance in the case *C*, and a standard lamp *D* and tripod *E*.

The instrument may be regarded as a photometer, in which, by simply rotating the eyepiece, a beam of selected monochromatic light from the hot body is adjusted to equal intensity with a beam of similar light from an incandescent electric

lamp. It is not a colour-matching device, but depends upon the application of the principle of the fourth power law of radiation previously referred to.

Behind the enlarged part in the front of the pyrometer in which is fitted the electric lamp are two holes. Light from the object under observation passes through one, and light from the lamp through the other. These beams of light then pass through a system of lenses and prisms, and are polarized in different planes, and rendered monochromatic. Finally the two beams of light pass through a single ocular. The observer sees an illuminated circular field divided into two semi-circles. One semi-circle is filled by an image of the hot body under observation, and the other is uniformly illuminated by the electric lamp. The two semi-circles are brought to an equal intensity of illumination by turning the eyepiece to which the scale pointer is directly attached. In this manner the unknown rays are compared with those of known intensity from an electric lamp.

The ammeter and regulating resistance supplied, ensure that the current through the lamp, and therefore the candle power, remains constant; the accuracy of the candle power may be readily checked in relation to that of a standard amyl-acetate lamp which is supplied.

The standard scales provided with this instrument range from 700° to 1400° C., 900° to 2000° C., 1200° to 2500° C., and 1400° to 4000° C.

Thermo-electric Pyrometers.

When the junction of a pair of dissimilar metals is heated an electromotive force is developed, and by measuring the amount of this potential, in the case of certain suitable metals, the temperature may be deduced.

The relation between the electromotive force E and the two temperatures T_1 and T_2 of the two elements of the couple may be expressed in the following form, namely:

$$E = a(T_1 - T_2) + b\ (T_1^2 - T_2^2),$$

where a and b are constants for the particular metals used, the values of which may be readily found by measuring the values of E, when the couple is inserted in substances of known melting points;* two observations only are necessary. It has been shown that for platinum and platinum-rhodium thermo-couples, the second term $b\ (T_1^2 - T_2^2)$ is practically negligible when temperatures exceeding about 300° C. are employed, so that the relation between the electromotive force and temperature T becomes a linear one and may be expressed as:

$$E = a_1 + b_1 T,$$

where a_1 and b_1 are constants.

The metals employed commercially for thermo-couples consist of "rare" metals, such as platinum and platinum alloys

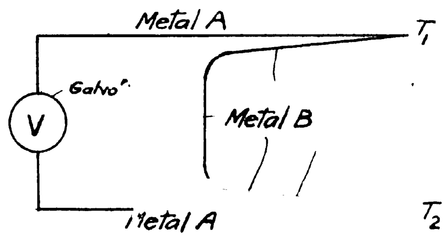


FIG. 254.

with rhodium and iridium, for measuring high temperatures, and "base" metals, such as iron and iron-nickel alloy, etc.†

The various temperature ranges corresponding to these metals are indicated in Table CXLII.

The use of rare metals is usually confined to scientific investigations and to the measurement of temperatures over about 1000° C., and of base metals for temperatures below 1000° C.

The thermo-couples are enclosed in quartz or porcelain tubes when the temperatures to be measured exceed about 800° C., and in steel sheaths when the base metal couples are used.

The "cold" junction of the couple T_2 (Fig. 254) is usually situated in the head of the pyrometer, and is provided with a shield, or protection of non-conducting material, so that the

* See p. 556. † For other thermo-couples see Table CXLII., p. 559.

junctions of the thermo-couples, terminals, and leads may all be at the same uniform temperature; in some cases the cold junction is water-cooled, so that the conditions of calibration

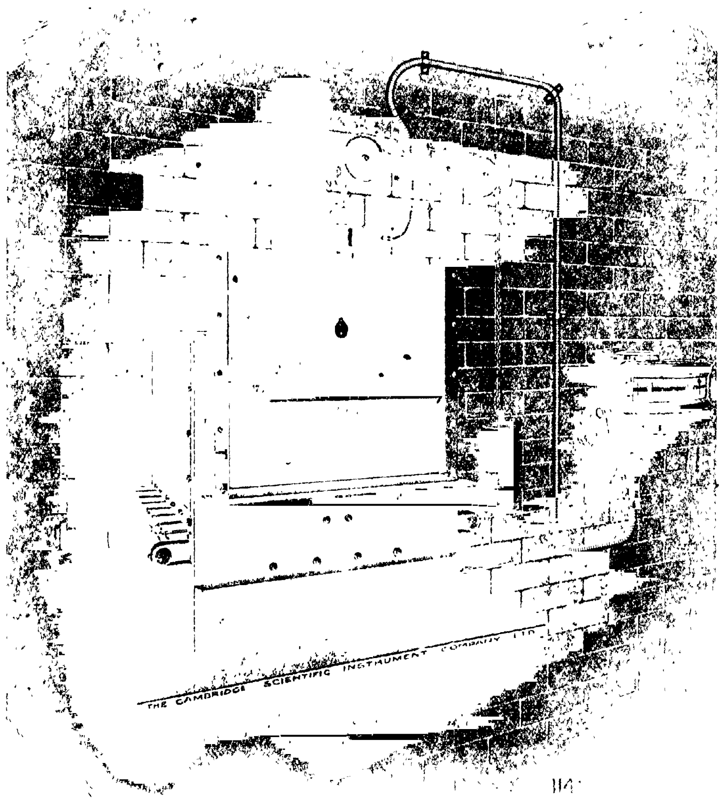


FIG. 255.—ILLUSTRATING METHOD OF USING THERMO-ELECTRIC PYROMETER OUTFITS.

are obtained. It should be pointed out that errors will arise if the cold junctions vary in temperature appreciably from their calibrated temperatures.

Twin, or twin-bore fireclay tubes are employed between the hot junction and the cold junction in order to insulate and to protect the wires.

The thermo-electromotive force may be measured either on a galvanometer or may be arranged to automatically record itself upon a chart. The types of direct-reading galvanometers usually employed commercially are the moving coil mirror or indicator types.

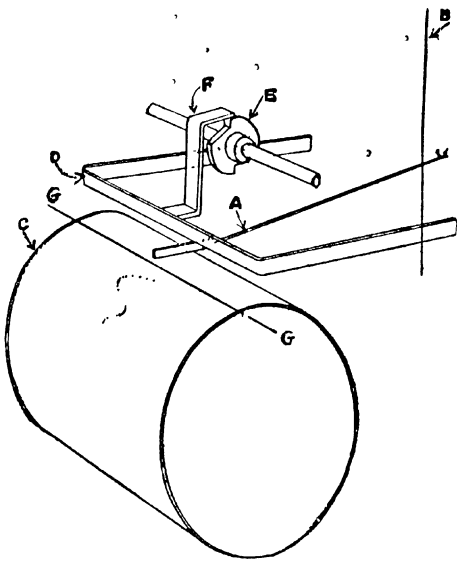


FIG. 256.

Fig. 255 shows a typical thermo-electric pyrometer outfit,* with a direct reading indicator type of galvanometer, whereby the temperatures of the furnace are read off directly on the scale.

Fig. 256 illustrates the principle of one of the best automatic temperature recorders, known as the "Thread Recorder," and in which the pointer A moving about an axis B of a suspended coil galvanometer is automatically depressed by clock-

* The Cambridge Scientific Instrument Co., Ltd.

work at definite intervals upon an inked thread G, which passes between the drum C and the pointer. In this manner an ink dot is made upon the slowly rotating drum C, corresponding to the temperature as indicated by the pointer.

Fig. 257 illustrates the complete recording apparatus, showing the drum with a temperature record chart in place; the drum in this case is arranged to make one revolution in either two hours five minutes or in twenty-five hours, by

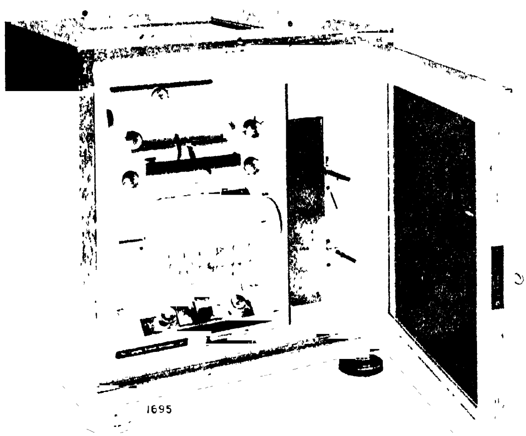


FIG. 257.—THERMO-ELECTRIC RECORDING APPARATUS.

means of a simple change speed device. The standard temperature ranges vary from 0° to 300° C. up to 0° to 1400° C. in six intermediate steps.

It is possible to arrange for two or more coloured inked threads to work upon the same drum, together with an automatic mechanism to switch in two or more thermo-couples and to bring the corresponding threads under the galvanometer needle, so that two or more records can be made upon the same chart.

It is an advantage of the thermo-couple that not only may the temperature at a point in a mass of metal be measured,

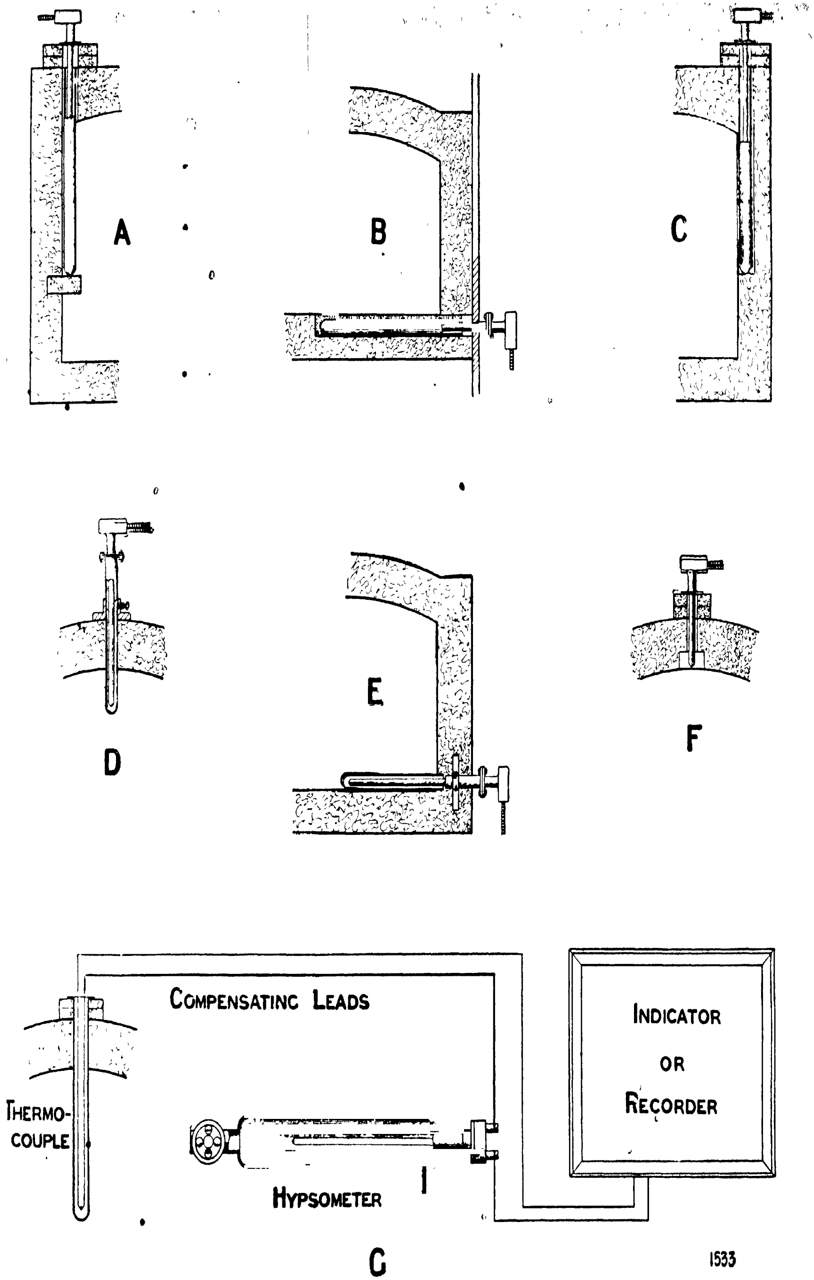


FIG. 258.—SHOWING ALTERNATIVE FURNACE POSITIONS OF THERMO-ELECTRIC PYROMETERS.

To face page 579.

but that, provided that the wires forming the junctions are the same, any number of pyrometers may be attached through a suitable switchboard to a single indicator; in this manner it is possible for one operator to ascertain the condition of a number of furnaces, from any selected spot, such as an office, provided with the necessary galvanometer or recorder.

The Electric Resistance Pyrometer.

The principle of this pyrometer* depends upon the fact that the resistance of a piece of platinum wire increases with the temperature, and that if the law of increase is known the temperature may be found by measuring the resistance.

Many substances, such as constantan,† show little, if any, resistance increase, whilst others, such as carbon, actually show a diminution as the temperature is increased; platinum in its pure state is, however, the only satisfactory metal to use for resistance pyrometers.

This type of pyrometer can be used for temperatures varying from $-200°$ to about $1200°$ C., and it is the most accurate type employed, for it is easily possible to measure temperatures to within one-tenth of a degree C.

The relation between the resistance R and temperature T may be expressed as follows:

$$R = a + bT + cT^2,$$

where a, b, and c are constants.

The relation between the platinum temperature p_t as measured upon the assumption of an uniform increase in resistance with temperature, and t the true temperature on the gas scale is given by—

$$t - p_t = \delta \left\{ \left(\frac{t}{100}\right)^2 - \frac{t}{100} \right\}$$

Where δ is a constant which has a value of about 1·5. This relation enables corrections $(t - p_t)$ to be found and applied to the observed readings.

It is usual to measure the resistance with a form of potentio-

* First used by Sir W. Siemens in 1871, and afterwards perfected and applied by Prof. H. L. Callendar.

† An alloy consisting of 60 per cent. copper and 40 per cent. nickel.

meter, or Wheatstone bridge, or to obtain direct readings with a form of Wheatstone bridge, known as the Whipple indicator, by means of which direct temperature readings may be obtained with great accuracy.

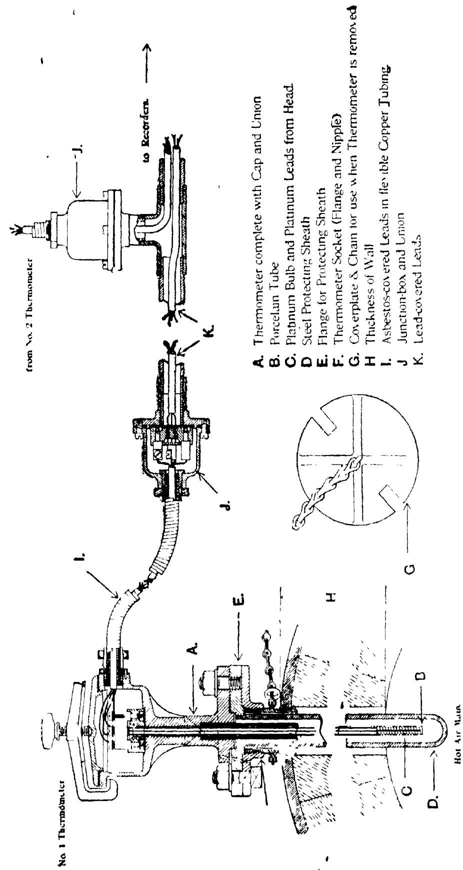


Fig. 259.—Illustrating the Principle of the Platinum Resistance Thermometer.

In the Callendar form of recorder, shown in Fig. 260, the principle of the Wheatstone bridge is employed, but instead of the bridge having to be balanced by hand, this is automatically done by means of the recorder mechanism.

In the usual form of resistance pyrometer the platinum wire is wound upon a cruciform-shaped mica frame, and the ends of the wire are connected to the head of the instrument by means of copper leads passing through mica disc insulators or separators. As the resistance of these leads varies with the temperature, and this effect would seriously affect the readings, a pair of exactly similar copper leads is provided and

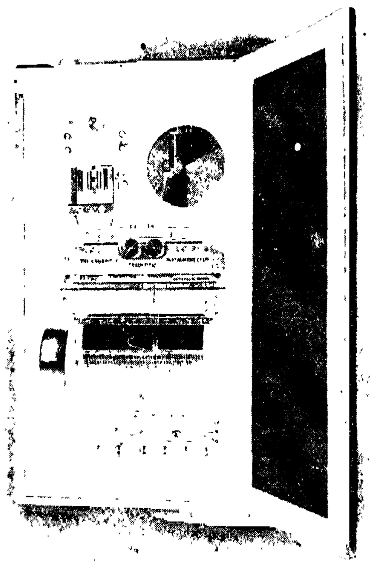


FIG. 260.—RECORDING APPARATUS USED WITH PLATINUM RESISTANCE THERMOMETER.

connected to another pair of terminals in the head, and thence to the opposite arm of the Wheatstone bridge; in this way the copper-lead resistance is automatically compensated under all conditions.

The platinum coil and leads are protected from the action of the furnace by enclosing them in a porcelain or quartz tube, usually with an outer removable steel sheath.

In the Cambridge form of instrument shown in Figs. 259 and 261 the terminals are enclosed in an aluminium head with a sliding cover, and the leads are brought out at right angles to the stem; in many cases it is necessary to employ armoured cables or leads for the first few feet leading from the pyrometer to a junction box, and to then continue from this box to the recorder with flexible-braided or lead-covered cable.

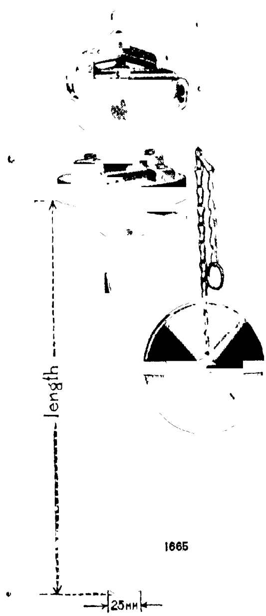


FIG. 261.—PLATINUM RESISTANCE THERMOMETER (OUTSIDE VIEW.)

In the Siemens resistance pyrometer the platinum wire is wound upon a special fireclay, and is protected from damage by surrounding it with magnesia and encasing it in an iron tube. A single compensating lead is employed, which is joined up in the measurement device so as to compensate for any variation in the ordinary leads.

In the Leeds-Northrup form of instrument the platinum

wire is wound upon lava, and a differential galvanometer is often used for measuring the resistance.

A type of indicating galvanometer and bridge known as Harris's indicator* is designed for use with the platinum pyrometer, and it possesses the advantage of giving temperature readings direct, without any experimental adjustment. A series of step resistances are provided, so that the temperature range can be varied by 100° C. at a time, and in the later forms an electrical control renders this process practically an automatic one.

* Made by Messrs. R. W. Paul.

CHAPTER XI

METAL JOINING PROCESSES

Metal Joining Processes.

METALS, either similar or dissimilar in composition, may be joined together in many ways, depending upon the compositions of the metals and the purposes for which the finished parts are required. The chief methods employed commercially are as follows:

1. *Soldering or metallic cement processes*, in which a solder of a lower melting point and dissimilar composition to that of the two metal parts to be joined is employed, and which forms a true alloy with the surface metal of the parts. This process includes soft soldering and hard soldering, or brazing.

2. *Autogenous fusing, or welding*, in which the two parts to be united are heated and liquid metal of the same composition is run around the mass, or the parts are heated to the fusion point and the surfaces are caused to adhere by pressure or by hammering.

3. *By cohesion*, under pressure, in which the perfectly clean surfaces are heated, but not to fusion point, and pressed together in a rolling mill or press.* This method is employed for joining soft metals, such as lead, iron, and steel, and for making compound sheets of different metals. For example, compound tin-lead sheets are used for domestic bottle capsules, aluminium-copper for spun work, and in the case of nickel and steel, copper and steel, nickel and zinc sheets, etc. This latter process is somewhat outside the scope of the present work.

The above methods (1) and (2) employ a wide range of

* A good example may sometimes be had in the case of cleaned iron sheets which have been annealed; it is often found that the bottom sheets are firmly united under the weight of the sheets above, and cannot be separated.

working temperatures, and, generally speaking, the higher the temperature of the process, the stronger will be the junction of the parts united. The following table will give an idea of the temperatures of the principal methods mentioned:

TABLE CXLVI.

TEMPERATURES AND APPLICATIONS OF DIFFERENT METAL JOINING PROCESSES.

Process.	*Temperature ° C.*	*Applications.*
Pewter soldering	90 to 130	For general pewter work.
Soft soldering (tinman's)	180 to 230	For pipes, tubes, brasses, unions, and most general purposes. Steel, copper, and brass.
Soft soldering (plumber's)	240 to 290	Plumbing work in general.
Silver soldering	800 to 950	For strong joints, petrol and oil unions, flanges, instrument work, aero. fittings, jewellery, etc.
Brazing ..	840 to 920	For iron and steel pipe work, flanges, repairs, bicycle lugs, clips, and fittings.
Electric arc welding	3400 to 3600	For tube and barrel manufacture, filling steel castings, boiler plates, cracks, and repairs.
Electric resistance welding	2000 to 3000	For rivet-welding, butt-welding, spot and roller welding barrels and containers, flanges, domestic ware, tubes, tanks, and all general work.
Oxy - acetylene welding	2400 to 2600	For general workshop and portablity purposes. Automobile repairs and fittings, aero. clips, sockets, etc. Tubes and barrels.
Oxy-coal gas welding	900 to 1500	Metal cutting, high-pressure fittings, etc. Thin plate work, lead-burning.
Oxy - hydrogen welding	1500 to 2200	Metal cutting, thin sheet metal work, lead work, building up worn surfaces, etc.
Thermit welding	3000	For large and outdoor repairs, rail joints, tyres, ship repairs such as sternposts, rudders, etc.

There is, of course, an appreciable latitude in the temperatures employed for soldering and brazing, depending upon the compositions of the solders themselves.

It is often inadvisable, and sometimes impossible, to employ the high temperatures required for welding, owing to the risk of internal stresses, and the "burning" of the metal in the case of alloy steels and alloys in general. Further, it is not always

possible to employ brazing processes for high tensile and alloy steels, which only develop their full strength after suitable heat treatment.

Soft Soldering.

For many aeronautical purposes, steel and brass tubing, plates, and other parts are conveniently soldered with a low melting point tin-lead alloy. The process possesses the advantages of (*a*) ease and convenience, without exceptional skill being required, and (*b*) freedom from the risk of affecting the temper or composition of the parts to be joined. Provided that suitable soldering areas are allowed, and that socket clips and similar parts to be soldered are properly designed,* very strong and permanent joints may be made.†

In the case of thin tubing joints, the low temperatures employed are not likely to affect the strength of the metal, or to oxidize same, as in the cases of brazing or welding.

The method employed for joining two parts by soft soldering is to first clean the parts thoroughly and then heat them to about 200° C. in a non-oxidizing flame or atmosphere,‡ the temperature being just above that of the fusion point of the solder itself. The solder is then applied either directly or upon a heated tinned-copper soldering bit, using at the same time a suitable flux (for dissolving the oxides and keeping the solder molten). The surfaces are each soldered in this manner, then heated to the same temperature as before, wiped or cleaned of superfluous solder, and pressed, pinned, or clamped together and allowed to cool.

It is essential to employ a good solder of tin and lead entirely free from *zinc*, as the latter thickens the solder and forms a scum or oxide, which the ordinary fluxes will not dissolve.

The layer of solder between the joints should be as thin as possible, and during soldering the surfaces, if flat, may be rubbed together, as it has been found that the "wetting" of

* See page 423 *et seq.*

† Aeroplane steel tubular fuselage frameworks, tail, rudder and control area frames, airship gondola frames, etc., are frequently built up of soft soldered and pinned tubes and sockets.

‡ Electrically heated soldering bits possess an advantage in this respect.

the surfaces is then more perfect, the joint accordingly being stronger. The soldering bit is useful for small articles and surfaces, but for larger parts, such as brasses, lugs, and fittings, the parts themselves should be carefully heated in a suitable muffle, bunsen, or blowlamp flame. Electrically heated bits are very convenient for small work, and possess the advantage of keeping the soldered or tinned portions clean.

Compositions of Soft Solders.

Most soft solders are alloys of lead and tin in different proportions, and with correspondingly different melting points.* Antimony is frequently present in tinman's solder, and gives a rather stronger joint.

The melting point of soft solder may be raised by increasing the lead content, and lowered by increasing the tin content. Lead melts at 325° C., whilst tin melts at 232° C.

The addition to tin-lead solder of bismuth, and in some cases of cadmium, increases the fusibility of the solder, that is to say, lowers the melting point. Thus, ordinary pewtering solders, which are amongst the most fusible of those employed for soldering, contain about 50 per cent. of bismuth, 20 per cent. of tin, and 30 per cent. of lead; it has the lowest melting point of the series—namely, 96° C.

Table CXLVII. gives the compositions of most of the soft solders used in practice, together with their principal applications, whilst Tables CXXV. and CXXVI. on p. 509 give the compositions and melting points of bismuth-tin-lead and lead-tin alloys, respectively.

A very useful lead-tin solder for tubular socket and general aeroplane work is one composed of 60 per cent. of tin and 40 per cent. lead; ordinary "Fluxite" paste forms a good fluxing medium.

Soldering Fluxes.

The function of the flux is to keep the surfaces to be united clean, by dissolving the oxides formed, and to promote greater fluidity in the melted solder.

* See Fig. 141.

TABLE CXLVII.

COMPOSITIONS AND MELTING POINTS OF SOFT SOLDERS.

Composition.			Melting Point. ° C.	Applications.
Tin.	Lead.	Bismuth.		
0	100	—	325	
10	90	—	305	
20	80	—	280	Coarse plumber's solder.
30	70	—	260	Fine plumber's solder for seams, angles, etc.
40	60	—	237	
50	50	—	212	Coarse tinman's solder, ordinary copper bit.
60	40	—	190	Fine tinman's solder, ordinary blow-pipe.
65	35	—	180	
75	25	—	183	Fine and hard solders for blowpipes.
80	20	—	186	
20	30	50	96	Pewter solder.

Fluxes may be either solid, liquid, or in the form of a paste. The liquid flux most commonly employed is that known as "killed spirits," or chloride of zinc; it is made by adding granulated zinc to hydrochloric (or muriatic) acid until all effervescence ceases. It is used principally for copper and brass-soldering work.

Another excellent liquid flux* is made by macerating flux skimmings from galvanizing pots with weak hydrochloric acid. The solution, after filtering, is ready for use, and is very suitable, on account of the presence of chloride of ammonia. Liquid fluxes are never employed in aeronautical or electrical work or in any instances in which there is any difficulty in thoroughly cleaning the soldered parts, owing to their corrosive or rusting effects; there is always present the danger of an excess of the acid, which will attack metals such as steel and brass.

Resin and tallow are examples of solid fluxes, and these are not open to the previous objections; they are chiefly employed for aeronautical and electrical work, and for lead and tin pipes. It is necessary to thoroughly cleanse the surfaces before using

* "The Joining of Metals," A. E. Tucker, *Journal of Inst. of Metals*, 1912.

these fluxes as, unlike liquid fluxes, they have no self-cleansing properties. There are many soldering pastes upon the market which are very convenient for soldering purposes, but in many cases zinc chloride forms a constituent, and the same precautions are necessary as in the case of the liquid fluxes.

A typical flux paste consists of starch and zinc chloride, mixed together until in the form of a paste; another widely used flux is made by mixing vaseline, or petrolatum, with saturated chloride of zinc in the proportions of 1 pound of the former to 1 ounce of the latter.

Solderine is the name given to solder in the form of tubes or hollow rods filled with resin, so that the solder and flux are combined.

Strength and Hardness of Solder.

The strength of a soldered joint depends upon the composition of the solder and upon the thickness of the layer of solder. For the best strength results the layer should be as thin as possible—namely, from 0·003 to 0·008 inch in thickness.

The strength of a properly soldered joint may be as high as 3·5 tons per square inch reckoned superficially—that is to say, the shearing strength; the average value may be taken as being about 2·5 tons per superficial inch, with 60 tin and 40 lead solder, using fluxite.

The hardness of various tin-lead solders* is given as follows:

TABLE CXLVIII.

HARDNESS OF TIN-LEAD SOLDERS.

Percentage of tin	0	10	20	30	40	50	60
Brinell hardness (500 kg.)	3·90	10·10	12·16	14·46	15·76	14·90	14·58
Percentage of tin	66	67	68	70	80	90	100
Brinell hardness (500 kg.)	16·66	15·40	14·58	15·84	15·20	13·25	4·14

* Kent's Pocket Book, p. 409.

Hard Soldering.

This process refers to the soldering of metals, using harder solders and higher temperatures, so that stronger joints result.

It is the method employed for making up tubular structures, such as bicycle frames, torque tube joints, etc., and where the temperatures employed are not detrimental to the metal parts it invariably gives a stronger joint. The process cannot always be employed with alloy and high carbon steel parts requiring special heat treatment afterwards.

Silver soldering is a process of hard soldering with a solder composed of copper, zinc, and silver, using powdered borax, or borax and carbonate of soda, as a flux. An excellent silver solder for strength and reliability is one compound of 60 per cent. silver, 23 per cent. copper, and 17 per cent. zinc; this solder is very liquid when molten, and therefore readily fills up interstices between the joints.

The following table gives the compositions of some typical silver solders:

TABLE CXLIX.

COMPOSITIONS OF SILVER SOLDERS.

Composition per Cent.			*Applications.*
Silver.	*Copper.*	*Zinc.*	
5 to 10	95 to 90	—	For thin iron and mild steel sheets.
45	55	—	A tough alloy for instrument makers, very fluid.
30	50	20	For small brass work.
38·5	46	15·5	For bronze and nickel silver.
9	43	48	For general work on copper alloys.
80	20	—	Hardest solder.
75	25	—	For general use.
50	50	—	Softest silver solder; will not burn.

Silver solders are employed for soldering iron, steel, copper, silver, gold, and their alloys; for soldering turbine blades into position; for high pressure and temperature small pipe connexions; for petrol pipe nipple joints; and similar purposes. For automobile and aircraft pipe joints and connexions, silver

solder is to be recommended, owing to its fatigue resistance and reliability; soft soldered petrol and oil-pipe joints invariably fracture with repeated vibration. Brass pipes are sometimes made by bending a sheet of brass into circular form through rollers or dies, and fixing the solder in the form of wire of suitable composition in the overlap with borax. On passing the work through a furnace in which it attains a red heat, the solder runs and makes the joint; the flux is then removed by dissolving, and the tube drawn through dies in the usual way. Joints in beaten metal work, such as the trumpets and horns of musical instruments, are made with hard solder of suitable composition, and colour.

Brazing.

Brazing is the name generally given to the process of hard soldering of copper, brass, iron, and steel with solders consisting of copper, zinc, and tin or nickel. The basis of most of these commercial solders, or "spelters" as they are termed, is brass, and their melting points range from about 840° to 920° C.

The higher the proportion of *zinc* in the spelter, the lower the melting point becomes, and the more applicable is the spelter for alloys of a low melting point; it does not pay, however, to employ more than about 45 per cent. of zinc, on account of the brittleness and weakness of the product.

The percentages of zinc for brazing iron and copper work are 35 and 40 respectively.

The composition of commercial brazing solders varies from 61 to 33 per cent. of copper, 39 to 60 of zinc, and from 0 to 14 per cent. of tin. Lead may be present up to as much as 3 per cent.

The higher the proportion of *copper* present the higher will be the melting point, whilst the effect of *tin* in spelter is to *whiten* it. Tin solders should not, however, be used for iron and steel owing to the deleterious effect of the tin upon the metals.

It is important that the composition of the brazing solder should approximate somewhat to that of the parts to be joined

for maximum strength conditions, as in the case of brazing solder for high pressure steam pipes.

The following are the compositions of some typical brazing solders:

TABLE CL.

COMPOSITIONS OF BRAZING SOLDERS.

Composition per Cent.				*Applications.*
Copper.	*Zinc.*	*Tin.*	*Nickel.*	
66	34	—	—	Hardest, suitable for iron and steel.
60	40	—	—	Hard, suitable for iron and copper.
50	50	—	—	Ordinary spelter, for brass and copper.
37·5	50	—	12·5	White solders, for nickel silver and iron
35·0	57	—	8·0	White solders, for nickel silver and iron
57·5	25	17·5	—	White solder for brass; more fusible than spelter.

Applications of Brazing.

Brazing is used for a large number of purposes in commercial work, but is not used to any great extent, except for repair work in automobile or aircraft work. Bicycle and car frames are often made up of separate components brazed together, the parts being pinned with special pegs in order to hold them together and in the correct positions. Brazing operations are usually conducted in a gas forge or brazing hearth provided with suitable temperature regulation means, and it is an advantage if a reducing atmosphere can be employed.

The borax flux employed leaves a very hard slag, or scale, upon brazed joints, which can only be removed by filing, pickling, or sand-blasting.

There are, at present, several methods of brazing in which the parts are dipped into a bath of molten spelter, the metal being prevented from adhering to the surfaces other than those to be brazed by coating them with blacking or similar compositions; these methods are economical and lend themselves to quantity production work. The joints made in this manner are more uniform, and there is no possibility of internal stresses

owing to the general nature of the heating, as distinct from the ordinary local heating of the blow-pipe or forge.

Another successful method is an electrical one; it consists in connecting the two parts to be joined with the terminals of a dynamo. When the current is switched on, the parts, on account of their high resistance, become heated to a brazing temperature, and the brazing wire, or spelter, which has been previously placed over the joint is melted, and fills the vacant spaces in the joint. With this system a reducing atmosphere of hydrogen, nitrogen, or coal gas may be employed, and fluxes dispensed with.

Pieces of high-speed tool steels are often hard-brazed into iron or mild steel shanks suitably milled out to receive them, using strips of copper between the joints to be brazed, and a special flux. The whole tool is then raised to the welding temperature of the copper, and the joint is made. The tool steel can then be hardened and tempered in the ordinary manner, since the temperatures employed are much below those of the melting point of copper. This method is probably applicable to other steel and iron joints.

Brazing Cast Iron.

In the ordinary way it is very difficult to braze cast iron on account of the carbon present, and of the oxides formed during the process; special fluxes are now available for cast iron work, and with special care fairly good joints can be made.

A process invented by Pich* for performing this operation in an ordinary smith's hearth, consists in decarburizing the surfaces of the cast iron parts to be united during the brazing, and in bringing the molten brass solder into close contact with the cast iron surfaces at the same time.

A copper oxide mixed with borax and in the form of a paste is used for decarburizing the surfaces; this paste is applied to the surfaces of the cast iron after they have been thoroughly cleaned. The parts to be brazed are held in position with iron wire and heated, when the borax is first melted and protects

* A description is given in "The Joining of Metals," by A. E. Tucker.

the surfaces from oxidation: it also prevents the copper oxide from being attacked by the oxygen of the air. As the heating proceeds the oxide of copper fuses and liberates its oxygen, which combines with the carbon of the cast iron, with the formation of carbon monoxide and dioxide, and the liberation of copper, which in its turn combines with the brazing brass; the new brazing compound, which now possesses a higher melting point, combines with the decarburized iron. Very strong joints giving almost the same tensile strength as that of the cast iron itself are obtainable with this method.

Welding Processes.

The principle of all welding processes consists in locally heating the surfaces to be united until the fusion point is reached, or in running liquid metal of a similar character into the joint.

The temperatures employed are high, being the fusion points of the metals themselves, and in some cases a higher flame temperature is necessary to take account of the loss of hea from the surfaces by conductivity, etc.

Welding processes are in general applicable to elementary metals such as iron, copper, aluminium, and lead, and joint of practically equal strength to that of the metal itself ar generally obtainable, with suitable precautions. For alloys such as carbon and alloy steels, bronzes, and aluminium alloys the results of welding are not always successful or reliabl owing to the composition of the metal at the surfaces of fusion being altered; it is well known, for example, that medium carbon steels are difficult to weld, and that high carbon steel are non-weldable.

Low carbon steels are readily weldable, but great care i necessary in order to prevent local overheating and the inclu sion of slag or oxide from the molten metal in the wel itself.

The properties of a welded joint cannot be stated from superficial examination, and very often what appears to be perfect joint from the welder's point of view will reveal seriou

defects under the microscope, or when subjected to tensile and bending tests.

Welding in Aeronautical Work.

In aeronautical work it has become the practice to employ welding processes for unimportant parts only, or parts in which the joint is in compression only, such as strut sockets, clips, engine plate stiffening ribs, compound edge-welded wiring plates, etc.; welded joints for important work should never be employed for tensile, shear, or bending stresses.

It is important also to avoid any internal stresses in the welded parts, due to the intense local heating at the joints: this may be partially remedied by an initial general heating of the parts, and by subsequent annealing. It should be added that several of the recent adaptions of electrical methods have given fairly consistent strength results, rendering them applicable to many hitherto precluded types of work.

Welding Methods.

There are four important methods of welding employed in practice—namely:

1. *Electric Welding*, using the electric arc, or the electric resistance heat.

2. *Flame Welding*, using the combustion heat or flame of gases or vapours, such as hydrogen, acetylene, benzol, or petrol.

3. *Thermit Welding*, in which the heat of combustion of powdered aluminium and iron oxides is utilized.

4. *Hand or Smithy Welding.*

These methods will only be briefly considered here owing to their somewhat limited application to automobile and aircraft work, although they are adaptable for repair work.

Electric Welding Methods.

There are several well-known electrical systems in use, depending upon the electric arc flame, or the electrical resistance methods; these methods in general necessitate the use of

special machines and fittings, which may be either fixed for production work, or portable for repairs and work upon large objects.

The *Electric Arc Method* consists in directing the flame of a carbon or metallic arc upon the parts to be welded, either by moving the carbons or by employing a magnet to deflect the flame.

The Carbon Arc Method.—The temperature of the carbon arc flame is about 3400° to 3600° C., according to the pressure employed, the former value referring to atmospheric pressure.

The metals to be welded are brought to the fusion point, and the joint is filled with the melted welding metal, which is in the form of a strip or rod. A direct current is nearly always employed, and as the heat upon the positive side of the arc is generated nearly three times as quickly as that from the negative side. The positive side forms the welding one.

In the *Bernardos* system the work is connected to the positive lead and the carbon rod forming the negative pole is fixed in an insulated holder. The arc is " struck " by touching the work with the negative carbon rod, which is then withdrawn to a certain distance depending upon the current used.

The voltage employed with the carbon arc systems is about 60, and the current varies from 50 to 500 ampères according to the class of work. A direct current only is employed for carbon arc systems. The diameter of the carbons varies from 0·5 to 1·5 inches according to the current value.

The current in this system is regulated both by means of a suitable regulating resistance and by manipulating the arc. The light and heat from the arc itself are very intense, so that the operator requires special gloves of the asbestos or heavy leather gauntlet type, and a mask or helmet provided with a screen for cutting off the ultra-violet rays.

The arc itself should be about 2 to 4 inches in length, and the operator should endeavour to hold the carbon at the correct distance for giving a steady and quiet arc; if the arc is too short the metal boils and spurts, whilst if it is too long the arc wanders, and much of the heat developed is wasted. The

material of the positive electrode (in this case, the work itself) is carried across the arc in the form of a vapour, and is deposited upon the negative pole; there is also some possibility of the carbon itself being deposited upon the molten metal of the weld during the process.

The carbon arc method has been successfully applied to the process of filling up blow-holes in steel or iron castings, and when properly carried out gives very satisfactory results.

Butt-joints are made by butting the pieces of iron or steel to be joined, and adding pieces of scrap of the same composition; the arc is then applied and worked along the joint, melting and fusing the scrap metal. The thickened joint is generally swaged whilst still at welding heat, the carbon and the swage being used alternatively. In the case of lap joints, metal is added so as to level off the angle end of the lap.

In the *Zerener* process the arc is struck between two carbons inclined at an angle to each other, and the arc formed is deflected on to the work by means of an electro-magnet; this is similar in effect to a blowpipe flame. There is a tendency with this system of carbon being carried on to the welded joint.

The carbon arc method has been successfully applied to the manufacture of steel oil drums,* tubes, boilers, cast iron repairs, copper welding,† and other work.

Metal Arc Systems.

There are several systems, such as the Slavianoff, Quasi-Arc, and Alloy Welding Processes, in which either a bare metal electrode is employed in place of the carbon one in the previous system, or a metal electrode covered with a refractory or fluxing material or a combination of both.

In the *Slavianoff or bare metal electrode system* the arc temperature is much lower, and the voltage required is also

* "Notes on Welding Systems," by J. Caldwell, Inst. of Engineers and Shipbuilders in Scotland, January 22, 1918.

† "Notes on Modern Methods of Electric Welding," by H. S. Marquand, *Journ. Inst. Elect. Engineers*, vol. liii., p. 851

lower (usually from 15 to 30 volts); the life of the arc poles is, however, much shorter.

With the metal arc systems the current may be either continuous or alternating, although the former is preferable.

The composition of the metal rod should be similar to that of the work to be welded, but suitable constituents may be added to the material of the rod to approximate to any desired composition in the metal of the weld.

In the metal arc system the positive pole metal is vaporized and projected upon the work, or negative pole; besides this action, molten metal portions from the smaller electrode may be projected bodily across the arc, and this fact is utilized in the process of filling the joint.

The bare metal electrode is necessarily at a red heat for some distance along its length, and therefore becomes oxidized on the surface by contact with the air in its passage across the arc, and this oxide often gets into the metal of the weld and forms flaws; moreover, the electrode dissipates a good deal of heat.

With metal arcs in general the heat of the flame is very much less than that of carbon arcs, but the energy consumption is smaller.

Coated Metal Electrode Methods.

The first improvement made upon the bare electrode method was to enclose the metal rod in a fireproof sleeve of a nonconducting material such as fireclay or special asbestos compositions, as in the *Kjellberg* system. In this case the metal is protected from oxidation and heat radiation, and as it is removed by the arc the sleeve projects beyond the arc and forms a guide for the molten metal; the sleeve automatically drops away as the metal melts.

In the Quasi-Arc and Alloy Welding Processes and similar methods, the process originally used by Stromenger—namely, of employing a sleeve to the metal electrode containing suitable fluxes is employed.

The flux melts as the arc is formed and covers the end of the electrode and also the weld joint, so that it protects it from

oxidation. The flux is frequently chosen* to contain constituents having a chemical action upon the fused metal, so as to improve its quality.

The coated electrode is usually clamped in a suitable holder and moved by hand along the length of the weld at an uniform rate, and with a sideways swinging motion across the weld, as in the blowpipe welding system.

The arc in this system is very short, being about one-eighth of an inch as a rule.

The composition of the coating varies with the material and the type of work. Usually the base of the coating is asbestos, and this material is impregnated with salts suitably chosen with the object of forming a mixed silicate flux or slag of suitable viscosity, and also for cleaning off the oxides. Either basic or acid silicates may be employed in the fluxes depending upon the metal welded.

The material of the electrode itself may also be varied to suit the work; for example, high speed or special tool steel pieces are sometimes welded to mild steel shanks with nickel-plated steel rods.

Aluminium wire or ribbon is sometimes wrapped around the rod before the flux coating is made; in one method the aluminium wire bound iron electrode is covered with blue asbestos spun yarn, and it is claimed that owing to the strong affinity of the aluminium for oxygen, a much stronger and cleaner weld is obtained. The proportion of aluminium to iron required is about 1 to 400 or 500.

Welding Data.

In a typical† coated electrode method of welding, the voltage required varies from 20 to 27, and the current from about 35 to 180 ampères, according to the thickness of the plate to be welded.

The following table shows the most suitable gauges of electrodes and currents for different thicknesses of steel plate or work :

* As in the methods of Alloy Welding Processes Ltd., London.

† The Equipment and Engineering Co., Ltd., London.

TABLE CLI.

Currents for Metal Electrodes.

Gauge of Electrode.	*Current in Ampères.*	*Thickness of Plate or Work (Inches).*
14	35	$\frac{1}{16}$
12	40	$\frac{1}{8}$
10	95	$\frac{3}{16}$ and $\frac{1}{4}$
8	140	$\frac{1}{2}$
6	180	1

Fig. 262 illustrates some of the principal types of joints employed in electrical welding, the black portions indicating the deposited metal.

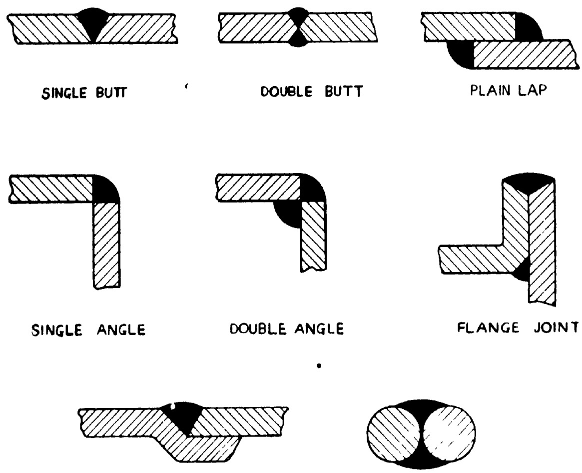


Fig. 262.—Showing Types of Electric Welds.

The speed of welding varies from about 15 to 50 feet per hour, depending upon the type of joint and the thickness of plate.

As an example may be quoted a typical case, in which two plates of $\frac{5}{16}$ inch thickness were welded together with a vee-

joint at the rate of 40 feet per hour, using 50 feet of 10 S.W.G. covered metal electrode, depositing about 1¼ feet of electrode per foot run of weld. The voltage employed was 105, and the current 105 ampères.

In another example two ⅛-inch plates were butt-welded at the rate of 24 feet per hour, the voltage being 105 and the current 50 ampères, 40 feet of 12 S.W.G. electrode being consumed.

Composition of Iron Electrodes and Deposited Metal.

The carbon and manganese content of the iron or mild steel electrode in the bare or coated metal method of welding is invariably reduced in amount by oxidizing, so that the deposited metal is almost pure iron.

The results given in Table CLII. have been selected from several sources.*

Preparation and Mode of Working.

The types of weld employed, as shown in Fig. 262, will depend upon the nature of the joints and the thickness of the metal. Butt-joints must be suitably prepared by veeing and fitting. Plates of less than ¼ inch do not require notching or veeing as the arc heat will penetrate to this depth. For thick plates both the angle and depth of vee must be greater in proportion, so that the electrode end is enabled to get down near the notch of the vee.

It is frequently necessary to apply several layers of weld in order to obtain the full thickness of the weld.

Where it is not possible to cut away the metal to form the vees, as in certain classes of repair work, a space should be left between the two joint faces to allow the metal to flow into the weld; a carbon electrode with reversed polarity can often be used for preparing the edges for welding.

* Notably from "Experiments on the Application of Electric Welding to Large Structures," by W. S. Abell, *Journ. of Commerce* (Liverpool and London), March, 1919. "Notes on Welding Systems," by J. Caldwell, Inst. of Engineers and Shipbuilders in Scotland, January 22, 1918.

TABLE CLII.

ANALYSES OF CORES AND DEPOSITED METAL. (Electric Welding.)

Type of Electrode.	*Composition of Welding Electrode.*					*Composition of Metal Deposited in Weld.*				
	Carbon	*Manganese.*	*Silicon*	*Sulphur*	*Phosphorus.*	*Carbon.*	*Manganese*	*Silicon*	*Sulphur.*	*Phosphorus.*
Roebling (bare metal)	0·16	0·56	0·016	0·032	0·024	0·05	0·18	0·011	—	—
Norway iron (bare metal) ..	0·049	0·021	0·08	0·007	0·025	0·05	0·018	0·011	—	—
Steel for shipbuilding repairs ..	0·136	0·350	0·110	0·030	0·015	0·030	0·037	0·020	0·031	0·020
Swedish iron, repairs	0·05	0·16	—	—	0·05	—	—	—	—	—
Quasi-arc (coated)	0·091	0·46	—	0·021	0·05	0·030	0·021	0·058	—	—
Double arc (coated)	0·085	0·35	—	0·054	0·108	—	—	—	—	—
E.E.C. (coated)	0·115	0·505	—	0·080	0·116	—	—	—	—	—

It is necessary to remove all rust, paint, scale, and dirt from the vicinity of the joint, otherwise the deposited metal may be weak.

Good electrical connexions should be made by means of suitable clamps.

In working, the bare end of the electrode, free from flux, should be placed in the holder, and the other end moved towards the work with a slight up-and-down motion, the rod being held at right angles to the work.

The electrode should momentarily touch the work to strike the arc, and as the metal begins to flow, the electrode should be moved down the joint with a zig-zag movement across the joint, feeding the electrode down as it burns away, so as to leave an uniform deposit.

The arc should be kept as small as possible, the end of the electrode being kept practically in the slag, which when the proper conditions of working are attained is a *bright red* colour, the electrode metal itself being a *dull red.*

Where an electrode is consumed before the joint is completed, the metal should be thinned out for a short distance, and thoroughly re-fused before proceeding again, taking care to remove the slag beforehand.

Several layers are often necessary, in which case the slag must be removed beforehand by chipping with light taps of a suitable hammer or tool and with a wire scratch brush.

The operator should wear a mask with non-actinic glasses, to stop the ultra-violet rays, and should be provided with asbestos or leather gauntlet gloves and an asbestos or leather apron.

Fig. 263* shows the methods of welding up steel barrels for withstanding internal pressures of about 100 pounds per square inch; the diagrams show alternative methods of joining cylinder ends with internal or external butt-straps.

The **Resistance Method** of welding is now widely applied in

* "Some Modern Methods of Welding," by J. T. Heaton, Proc. Inst. of Mech. Engrs., February 20, 1914.

the manufacture of metal articles, more particularly for sheet metal parts, such as half-stampings, which have been made separately, and require assembling together afterwards.

The heat is generated by the passage of a current of high ampèrage, and of low voltage through the joint, and it is usual to employ a single phase alternating current for this class of welding. The voltage generally varies from about 2 to 8 or 10 in resistance welding.

There are three principal methods of welding—namely, *Butt* or *Contact*, Seam or Roller, and *Spot* welding, and there are now special machines upon the market for the purposes.

In **Spot Welding** processes the work is placed upon a fixed copper contact piece or electrode, and a second movable

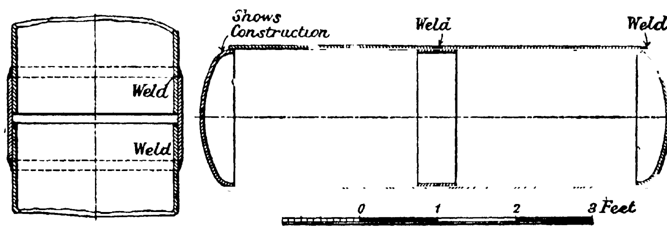


FIG. 263.—EXAMPLE OF STEEL BARREL WELDS.

electrode is held or pressed upon it; when the current is turned on the work is heated to a welding heat at the desired places. The process is akin to riveting, except that the sheets or parts are joined at spots by local welding instead of by rivets. The electrodes vary in shape according to the nature of the work, and in spot-welding machines the electrodes are pressed on to the work by means of a foot-operated lever, which also automatically switches on a low voltage current welding the surfaces under the electrode. The work is then moved along, after the foot lever is released, to the next position.

For plate welding as many as 1000 welds or spots per hour can be done in one of these machines, either foot or mechanically operated.

Spot welding is employed in the manufacture of all kinds of

work, in place of riveting; for example, buckets, kettles, pans, stoves, galvanized iron work, etc.

Seam Welding.

This is similar to spot welding, but it is continuous instead of being intermittent, so that fluid-tight joints can be made. The method is applicable to thin metal sheet work; it includes the process known as *roller welding.*

The electrodes in this case are in the form of rollers, through which the two sheets are passed, and the current is turned on as the work proceeds, heating up the metal of the two sheets over the width of the rollers to a welding heat.

The pressure between the rollers whilst the heated work is passing is sufficient to unite the metal sheets.

The continuous seam joint is stronger than in spot-welding, and can be rapidly made; it is essential, however, that the surfaces to be welded must be quite clean, either pickled in acid or sand-blasted.

Butt Welding.

In the *Thomson-Houston* process of contact welding a heavy alternating current is passed through the joint, raising it to the welding temperature.

Contact welding, in which a continuous seam, or butt, is welded, is applied to gas and watertight joints. In these cases, the work is caused to travel slowly under the electrodes, so that a progressive or continuous welding occurs.

In this method of joining bars, rods, rail-sections, and other objects by direct abutment, the pieces are clamped or held together end-on, the clamps forming part of or being connected to the transformer low-pressure winding.

When the current is switched on, the joint is heated to welding point and pressure is applied* by means of a lever-system, ratchet, or hydraulic system.

The pressure and current are maintained until a distinct burr

* An example of electric butt welding in the case of aluminium is illustrated in Fig. 270 on p. 628.

is formed at the junction, showing that plastic flow at fusion temperature has taken place and that any oxides or slag has been squeezed out.

The weld is usually hammered whilst still red hot. It is sometimes desirable to increase the current passing as the welding progresses, in order to keep up the temperature as the contact resistance approaches that of the pure metal. This is carried out by means of a regulating resistance and an ammeter in the primary circuit of the transformer.

This method of welding is used for joining all kinds of rods and bars, steel rails, and tyres, wire and tubing in manufacture and in cable making, etc.

Steel barrels, boilers, receivers, tubes, plates, rims, such as those of bicycles, half-stampings, domestic utensils and other objects may be satisfactorily welded by the butt or contact method; it is important, however, that the metal parts should not be too thick or of irregular thickness.

General Notes.

Welds are usually made much quicker by the electric processes, and the joints are capable of withstanding high pressures in the case of drums and receivers. For example, welds have been made in gas cylinders which have successfully withstood a pressure of 4000 pounds per square inch, and in mild steel tubes of $\frac{3}{16}$ inch thickness by $1\frac{1}{4}$ inches inside diameter, which have withstood an hydraulic pressure of 6 tons per square inch.

Electric welding, once the plant has been installed, is much cheaper and cleaner for many classes of work, particularly for quantity production and standard articles, but the initial plant cost is much higher than that of most gas welding plants. The electrical methods are not in general suitable for small and complicated shapes such as those employed in aeronautical work.

The following table gives some of the results obtained* by

* *Iron and Trade Review.*

butt welding round rods varying from $\frac{1}{4}$ to 1 inch in diameter, electrically, in the shortest and longest times respectively.

TABLE CLIII.

ELECTRIC BUTT WELDING RESULTS.

Diameter of Iron Rod.	*Time in Seconds.*		*Current (Amps.).*		*Volts per Square Inch.*	
	Least. A.	*Greatest. B.*	*A.*	*B.*	*A.*	*B.*
$\frac{1}{4}$	2·7	5·0	1960	1645	39·5	35·5
$\frac{3}{8}$	4·0	5·27	4330	2190	45·5	19·7
$\frac{1}{2}$	4·0	15·8	6600	1800	36·6	13·0
$\frac{9}{16}$	3·6	21·5	8400	3400	8·0	12·25
$\frac{5}{8}$	3·5	10·85	9400	5510	33·7	18·85
$\frac{3}{4}$	4·0	22·2	10,000	9400	16·3	19·7
$\frac{7}{8}$	7·0	17·0	11,900	10,550	27·7	19·6
1	33·0	114·0	7740	4450	10·4	16·1

Gas Welding Systems.

There are four important gas welding processes—namely, (1) the Oxy-Hydrogen; (2) the Oxy-Acetylene; (3) the Oxy-Coal Gas; and (4) the Oxy-Benz systems.

The two latter systems are not employed to any extent in engineering work at present, but the last-mentioned process possesses the advantage that it gives a higher flame temperature than that of the oxy-hydrogen system, and that it is more convenient to use a liquid fuel in practice owing to its compact and portable nature.

The oxy-coal gas system is largely employed in lead-burning and is economical, but the impurities in coal gas usually have a detrimental effect upon the metal welded; the flame temperature is about 30 per cent. lower than that of the oxy-hydrogen one.

(1) The Oxy-Hydrogen Process.

The process of combustion of hydrogen and oxygen results in the formation of water in the form of steam, one volume of oxygen being required to two of hydrogen for perfect com-

bustion theoretically. In practice, however, a large excess of hydrogen is employed (usually from four to five volumes of hydrogen to one of oxygen) in order to produce a *reducing* flame—that is to say, to prevent oxidation of the metal.

The effect of the excess of hydrogen is to reduce the flame temperature from about 2000° to about 1500° C., so that the process is not applicable to metals having a high conductivity and melting point, for a considerably higher flame temperature is then required.

The calorific value of hydrogen completely burnt in oxygen is about 350 B.T.U.'s per cubic foot, but, owing to the excess of hydrogen necessary, this value is appreciably reduced in practice.

Oxy-hydrogen welding has been employed for thin iron and steel sheet and pipe work, as the flame is more diffused and less intense than in the case of oxy-acetylene, and the metal is therefore not so readily burnt or over-heated.

The oxygen and hydrogen employed for this process must be very pure, and it is therefore usual to employ the electrolytic gases.

(2) **The Oxy-Acetylene Process.**

In this process the two gases oxygen and acetylene (C_2H_2) are led under pressure* into a common blowpipe, provided with independent regulating valves, and is ignited at the outlet, forming an intensely hot flame; the temperature of which can be varied from 2000° to 2500° C.

The heating value of acetylene is about 1500 B.T.U.'s per cubic foot, and it consists approximately of 92·5 per cent. carbon and 7·5 per cent. oxygen.

When burnt in oxygen the following are the chemical reactions :

$$2C_2H_2 + 5O_2 = 2H_2O + 4CO_2,$$

that is to say, two volumes of acetylene require five of oxygen for complete combustion, and the products of combustion con-

* This is termed the high pressure system. In the low pressure system only the oxygen is delivered under pressure, and by an injector action draws the acetylene gas into the burner.

sist of four volumes of carbon-dioxide and two of steam or water vapour.

Acetylene gas is made, commercially, by the action of water upon calcium carbide (CaC_2), the chemical reaction being as follows :

$$CaC_2 + H_2O = CaO + C_2H_2.$$

One pound of calcium produces 4·5 cubic feet of acetylene, and if the carbide is decomposed at the rate of 4 pounds per hour, about $6\frac{1}{2}$ gallons of water will be required for every 6 pounds of carbide decomposed.

Actually it is found necessary to use about four volumes (instead of two) of acetylene to five of oxygen.

In consequence of the high flame temperatures, the water formed by the primary combustion is dissociated into hydrogen and oxygen, and the latter element combines at once in the flame with the carbon of the acetylene to form carbon-dioxide, leaving the hydrogen to combine only with the oxygen which has passed out of the hottest flame zone; so that it does not involve a consumption of heat at the expense of this zone.

It is thought that the hydrogen, which is not able to combine with the oxygen in the inner flame zone owing to the high temperature existing (which is above the dissociation temperature) remains temporarily in a free state and partially protects the inner zone from heat loss by radiation, whilst preventing any tendency of oxidation.

The reason for the difference between the actual and the theoretically larger volume of oxygen required lies in the fact that the temperature of combustion is much higher than that of the dissociation of the steam, and as a result the hydrogen in the acetylene passes to the outer edge of the welding flame where it is cooled by the air, and also extracts oxygen from it, burning at a reduced temperature and forming water vapour in the process.

Production of Acetylene.

There are two systems used for oxy-acetylene welding namely, the *high* and the *low* pressure ones.

The High Pressure System consists in using both of the gases under high pressure, the acetylene being supplied dissolved in *acetone*, or a porous material soaked in acetone.

Acetone is a liquid hydrocarbon which can absorb about 25 times its own volume of acetylene gas at atmospheric pres-

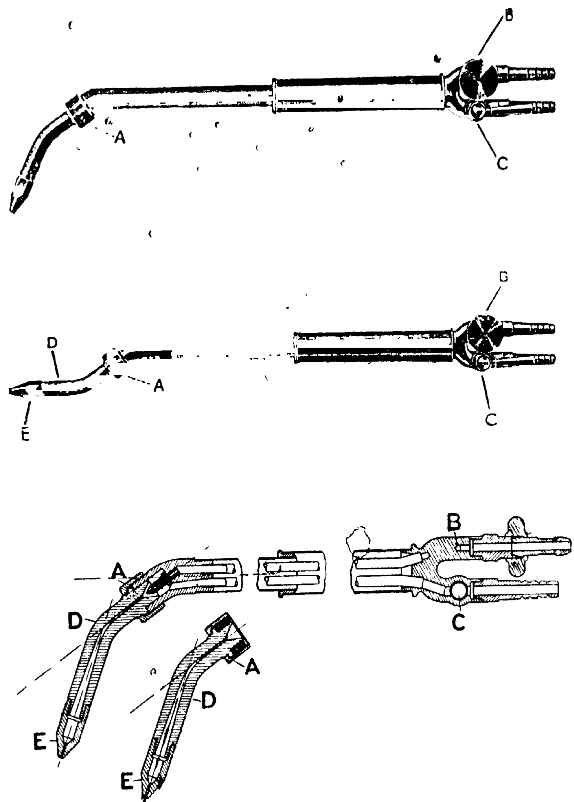


FIG. 264.—INJECTOR BLOWPIPE FOR OXY-ACETYLENE WELDING.

sure, and for each increase of atmospheric pressure the volume absorbed is increased some ten times, so that the cylinders which are usually supplied at 10 atmospheres pressure can contain 250 times their volume of acetylene; for practical reasons, however, they are only filled with 100 volumes.

With this system acetylene can be supplied in a pure state, whereas in low pressure systems the gas must be carefully freed from all impurities for welding purposes.

The Low Pressure System, which is the one most commonly employed, uses acetylene gas generated on the spot from calcium carbide in a special generator.

The oxygen is supplied in cylinders usually of 100 cubic feet capacity (of free gas), and of from 98·5 to 99·5 per cent. purity, at 120 atmospheres pressure. A special injector form of blowpipe is employed, in which the flow of the oxygen under pressure, through a special injector nozzle* *A* (Fig. 264) induces a supply of low pressure acetylene through the pipe leading from *C*, and the two gases may be mixed in any proportions by means of the regulating valves *B* and *C*. A variety of different nozzles are supplied, usually differing in the shape and size of the portions *D* and *E* for different work.

It is stated that with the type shown in Fig. 264 a negative pressure or suction of from 5 to 14 inches of mercury can be obtained. The following table gives the approximate gas consumptions for different mild steel plate thicknesses for different sizes of blowpipe.

TABLE CLIV.

ACETYLENE AND OXYGEN GAS CONSUMPTIONS.
(British Oxygen Company.)

No. of blowpipe ..		2	3	4	5	6	7	8	10	12	15
Approximate thickness of plate joint ..		*in.* 1/32	*in.* 3/64	*in.* 3/32	*in.* 1/8	*in.* 3/16	*in.* 9/32	*in.* 3/8	*in.* 1/2	*in.* 3/4	*in.* 1
Approximate consumption of gases per hour in cubic feet ..	Oxygen	*c. ft.* 1·75	*c. ft.* 3·0	*c. ft.* 6·5	*c. ft.* 9·0	*c. ft.* 16·0	*c. ft.* 23·0	*c. ft.* 34·0	*c. ft.* 48·0	*c. ft.* 75·0	*c. ft.* 100·0
	Acetylene	*c. ft.* 1·2	*c. ft.* 2·0	*c. ft.* 4·5	*c. ft.* 6·3	*c. ft.* 11·2	*c. ft.* 16·0	*c. ft.* 24·0	*c. ft.* 34·0	*c. ft.* 52·0	*c. ft.* 70·0

Note.—The above gas consumption figures are average results obtained when working on cold steel plates. In the thicker sections a considerable saving can be effected by pre-heating in the region of the joint.

* The British Oxygen Co.

Acetylene Generators.

Generators for low pressure acetylene should be of the correct proportions, for too small a generator will result in much heat being evolved; and, apart from the dangers of the higher pressures, the acetylene may be decomposed into other hydrocarbons; in any case the temperature of the gas should not exceed 100° C. on leaving the carbide.

The generation of acetylene should be slow and regular, and the rate of decomposition should not exceed about 4 pounds of carbide per hour.

In the *water-to-carbide* type of generator which is widely used, the carbide is placed in a number of separate boxes or compartments, and water is admitted to each compartment in turn, so that when one charge is exhausted the next is attacked.

Fig. 265 illustrates, in section, a common type of acetylene generator used for low pressure welding.* It consists of a cylindrical body or water reservoir in which floats a gas-holder suitably guided by means of rods. The carbide chambers are situated in the bottom of the tank, so that the gas generated is cooled by the surrounding water. The carbide chamber is subdivided by partitions *G* into compartments, as explained above, so that the carbide in one box only at a time is acted upon by the water. The water supply to the carbide is automatically regulated by the rise and fall of the gas-holder, which actuates a valve controlling the supply of water. The acetylene generated is partially purified by washing, and the moisture is removed in a condensing chamber, after which it passes into a purifier in a separate compartment.

Purifiers.

The best known purifiers are *Heratol* and *Frankolin,* the former being a chromic acid solution which is capable of removing sulphur, phosphorus, and ammonia, changing its colour as it becomes "spent" from orange to green; one pound

* *Aëronautics,* August 23, 1916.

of heratol will purify about 110 cubic feet of acetylene. This purifier attacks metals, so must be used in earthenware or enamelled vessels. Frankolin is a solution of cuprous oxide in

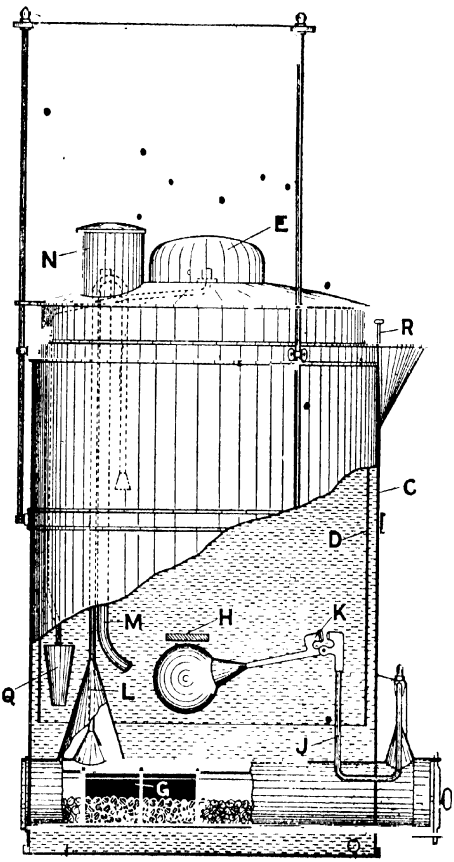


FIG. 285.—ACETYLENE GAS GENERATOR.

strong hydrochloric acid, absorbed in porous earth, and is capable of purifying about 100 cubic feet of gas per pound. It should also be only used in earthenware or enamelled containers.

Another impurity in acetylene gas is phosphoretted hydrogen, which must be removed, owing to its deleterious effects upon the metal of welded joints.

Back Pressure Valve.

All acetylene generators are now supplied with an "*hydraulic back-pressure valve*," which is fixed on the acety-

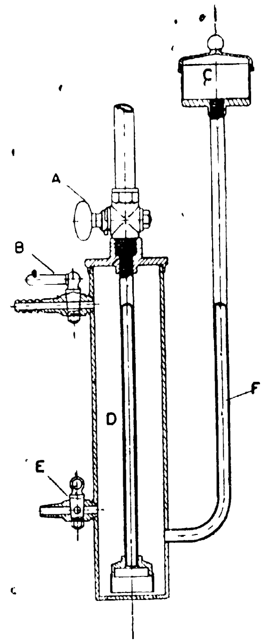


FIG. 266.—HYDRAULIC BACK PRESSURE VALVE.

lene supply pipe in a vertical position, as close to the blowpipe as can be conveniently done; the function of this valve (Fig. 266) is to prevent the oxygen from flowing back along the acetylene pipe, and thereby forming a dangerous explosive mixture. The acetylene inlet and outlet pipes are shown at *A* and *B* respectively. Water is poured through the funnel *C*, which is provided with a loose-fitting cap until the chamber *D*

is filled to the level of the tap *E* which is used as a level-indicator. The pipe *F* should be long enough to give a greater water pressure than that of the acetylene gas (that is, greater than about 8 inches). If the blowpipe nozzle becomes choked at any time whilst the oxygen tap is open, this gas will be forced along the pipe leading to *B*, and the back-pressure will act on the surface of the water in *D* and force the water up the pipe *F*, displacing the lid *C*, so that both gases will escape into the atmosphere until the taps *A* and *B* are closed.

Acetylene generators for workshop purposes are usually made in capacities of from 200 to 300 cubic feet, and for larger capacities they are arranged in a series so that when one be-

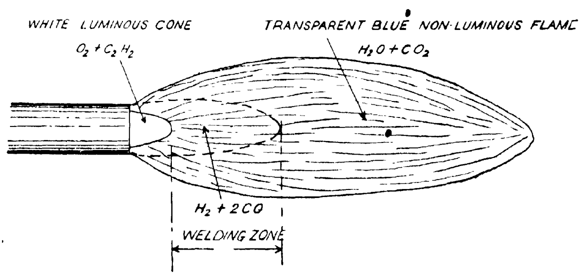


FIG. 267.—THE OXY-ACETYLENE FLAME

comes exhausted, the action automatically proceeds to the next, without any interruption in the supply. The exhausted chambers can be recharged without interfering with the other generators.

The Blowpipe Flame.

The blowpipe is "started," by turning both oxygen and acetylene taps full on and lighting at a small wick lamp; the acetylene is then in excess, so that it must be gradually turned off until there is a clearly defined cone at the orifice, varying in height or length from ¼ inch to ¾ inch, according to the size of blowpipe. Fig. 267 shows the type of flame obtained with oxy-acetylene. If the oxygen is in excess the

flame becomes pale in appearance, and short, and when applied to the metal to be welded causes a discharge of sparks.

An excess of acetylene causes a black (carbon) deposit around the welded area, and the flame becomes much longer and of a brilliant red-white appearance, with a green cap over the inner cone. The best flame condition is the one giving the greatest heat, slightly reducing in character, and with a well-defined inner cone with a pale outer flame.

General Welding Notes.*

The parts to be welded should be well cleaned of all scale and in cases of butt, or edge, welds (Fig. 268) the metal may be chamfered, so as to give a greater area, and to permit of more intimate contact with the welding rod or strip metal when fused.

The composition of the welding strip should approach that of the parts to be welded; it is usual to employ shearings of the same metal, or pure Swedish iron wire.

In the case of thicker plates, care should be taken to melt the edges inwards for at least one-quarter of the plate thickness, whilst adding the additional metal from the feeding wire Light hammering of the weld in the case of iron and steel, whilst red hot (900° to 1000° C.) will usually improve its quality and strength, but hammering should not be done below a black-hot temperature

All parts to be welded should, if possible, be pre-heated before welding, in order to minimize temperature stresses.

All welded parts should be annealed at 850° to 900° C. to remove internal stresses due to unequal heating and cooling. For thin plate welding, the flame should be a reducing one, and great care is necessary to prevent "burning," by raising the flame immediately fusion has occurred.

Alloy and high carbon steels cannot be properly welded by the ordinary method, as these metals have a lower melting point which approximates to that of the oxides of iron formed, so that, instead of the oxide fusing before the metal as in the

* For oxy-acetylene welding.

case of iron and mild steel, and rising to the surface, it remains imprisoned in the weld metal; it is necessary to use a special deoxidizer, as in the case of cast iron.

The procedure, when welding is finished, is always to close the combustible (in this case, the acetylene) gas tap first. The burners become hot during welding and should be occasionally cooled in water.

Provision should be made for the escape of the carbon dioxide gas combustion products when working in confined spaces.

It is essential for workmen to wear tinted or blue goggles whilst welding.

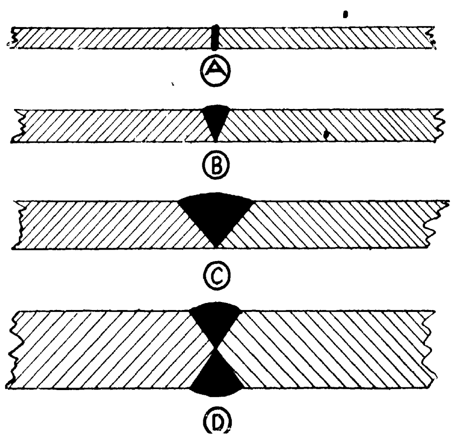


FIG. 268.—TYPES OF PLATE WELDS.

Types of Welded Joint.

Fig. 268 shows some of the principal methods of making welds.

When the plate thickness is less than 16 S.W.G. (·064 inch) the ordinary straight butt weld is used, as shown in (*A*), Fig. 268. For thicknesses between 16 S.W.G. and 0 S.W.G. (about $\frac{1}{4}$ inch) the edges are bevelled to about 45°, as shown in (*B*), Fig. 268.

Between about $\frac{3}{16}$ and $\frac{5}{16}$ inch the angle of the bevel should

be about 90°, as shown in (*C*), Fig. 268, whilst for thicker plates it is advisable to double-bevel the edges, as shown in (*D*), Fig. 268, the angle of the bevel increasing with the thickness to a certain extent.

Speed of Welding.

The following table gives the average rates at which welding can be done with mild steel plates of varying thicknesses, together with the gas corresponding consumptions.

It will be observed, that the speeds are roughly inversely proportional to the plate thickness, and that the gas consumption varies as the plate thickness.

TABLE CLV.

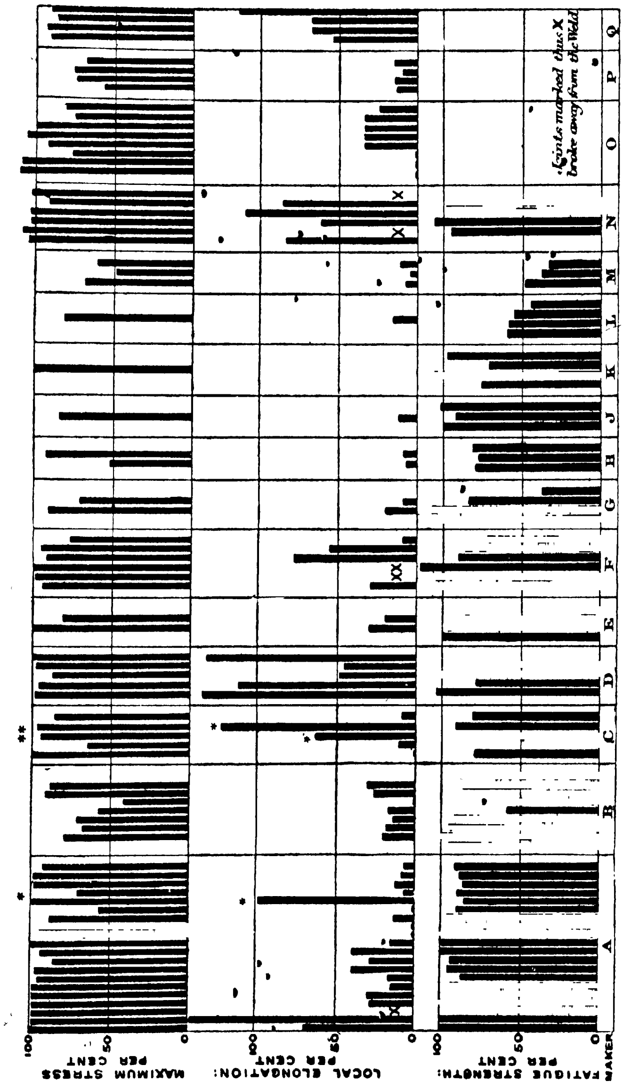
RATES OF WELDING OF MILD STEEL PLATE AND GAS CONSUMPTIONS.

Thickness of Plate.	*Approximate Run per Hour in Feet.*	*Oxygen Pressure, Pounds per Square Inch.*	*Consumption per Hour in Cubic Feet.*	
			Oxygen.	*Acetylene.*
$\frac{1}{32}$	40	5	2	$1\frac{1}{2}$
$\frac{1}{20}$	38	6	3	$2\frac{1}{2}$
$\frac{1}{16}$	26	7	$3\frac{1}{2}$	3
$\frac{1}{8}$	14	8	6	$4\frac{1}{2}$
$\frac{3}{16}$	12	$11\frac{1}{2}$	8	6
$\frac{1}{4}$	9	14	16	12
$\frac{3}{8}$	6	$17\frac{1}{2}$	29	20
$\frac{1}{2}$	5	22	35	28
$\frac{5}{8}$	4	$24\frac{1}{2}$	45	35
$\frac{3}{4}$	$3\frac{1}{2}$	27	55	42
1	3	30	78	63
$1\frac{1}{4}$	$2\frac{1}{2}$	$32\frac{1}{2}$	92	73
$1\frac{1}{2}$	2	35	106	82
2	$1\frac{1}{2}$	40	125	100

The Strength and Testing of Welded Joints.

The tensile strength of a welded joint varies from about 70 to 75 per cent. in the case of thick plates up to 85 to 95 per cent. for thin plates, when the joint is properly made.

The strength of a joint is, however, to a large extent, dependent upon the skill and experience of the individual welder,



PROPERTIES OF WELDED JOINTS IN TERMS OF THOSE OF THE ORIGINAL MATERIAL.

(NOTE.—*In the three cases indicated thus * the ordinary visual evidence of welding was not apparent before or after the test.*)

FIG. 269.—STRENGTHS OF WELDED JOINTS.

and for this reason, whilst some joints may be practically as strong as the original metal, others may, on the other hand, be considerably weaker; it is the weakest possible joint that determines the strength of a welded structure, so that considerable care must be taken in employing such structures for taking tensile and bending loads.

In aeronautical work welds should never be allowed to take any important loads in tension or bending.

A series of tests which were made upon welded joints made by hand, acetylene, and electrical processes, gave the results shown graphically in Fig. 269, in which the thick black ordinates represent, in height, the properties indicated on the side of the diagrams. The following table gives particulars of the processes by which the joints were made.

The joints were tested in tension and in repeated bending upon the Wöhler type* of fatigue testing machine, and their properties were compared with those of the original unwelded material. Fig. 269 shows (1) The *tensile strength* of each joint expressed as a percentage of that of the original material; (2) the *local extension* expressed as a percentage of that of the original material; and (3) the *fatigue strength* of hollow specimens in terms of that of the original material.

The want of uniformity in the heights of the ordinates, taken as a whole, shows that whilst a good percentage of the joints are nearly as strong as the original metal, yet several are considerably weaker, and no guarantee can be had of any particular joint being uniformly as strong as the original metal.

The variable nature of the elongations is also an indication of the want of uniformity of ductility at the joint. It may be added that these joints were made and supplied by a number of different manufacturers, the names of whom were designated by the letters in the first column of Table CLVI.

A good workshop test of a welded joint consists in hammering over the welded joint, or to hammer and break the superficial scale, and to apply petroleum to the weld. If there is any crack, the petroleum will quickly soak through and show up

* See Fig. 104, p. 212.

TABLE CLVI.

PARTICULARS OF WELDED JOINT TESTS.*

Designation.	Material.	Particulars.
A	Wrought iron and mild steel	Hand-welded and electrically welded, 40 joints in all.
B	Low carbon steel 0·22 carbon steel 0·57 carbon steel	Joints hand-welded, using silver sand and scarfing. 16 joints in all.
C	0·006 carbon steel	6 hand-welded rivet steel joints. 6 electrically welded rivet steel joints. (Thomson process).
D	Wrought iron	6 hand-welded joints.
	Mild steel (0·217° C.)	6 ,, ,,
E	Wrought iron	3 ,, ,,
	Mild steel bar (0·171° C.)	3 ,, ,,
F	Wrought iron	6 ,, ,,
	Mild steel (0·175° C.)	6 ,, ,,
G	Wrought iron	3 ,, ,,
	Steel (0·222° C.)	3 ,, ,,
H	Steel (0·204° C.)	6 ,, ,,
J	Wrought iron	6 ,, ,,
K	Mild steel (0·056° C.)	6 electrically welded joints.
L	Wrought iron	6 oxy-acetylene welded joints, using mild steel wire for feeder, and slightly hammering after welding, then annealed.
M	Steel (0·207° C.)	6 ditto.
N	Wrought iron	6 hand-welded joints.
	Steel (0·158° C.)	6 ,, ,,
O	Best chain iron	6 ,, ,,
	,, ,,	2 electrically welded joints.
P	Yorkshire wrought iron	3 hand-welded joints.
	Staffordshire wrought iron	3 ,, ,,
Q	Wrought iron	6 ,, ,,

by a black patch the exact locality. Another method of detecting flaws or cracks is to electro-plate the part, when any surface crack or defect can be readily seen.

Closed vessels for containing liquids or gases should be subjected to an hydraulic test.

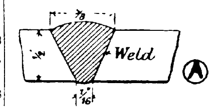
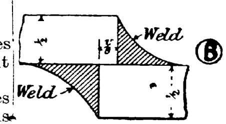
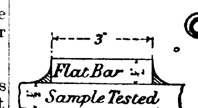
The tensile strength of electrically welded joints, properly executed, and as used in production work, has been given† at 89 to 96 per cent. of that of the original metal.

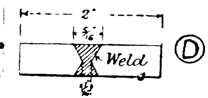
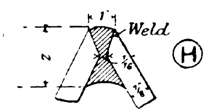
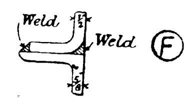
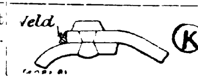
* "The Strength of Welded Joints in Iron and Steel" (Stanton and Pannell), Proc. Inst. Civil Engrs., 1912.

† "Modern Methods of Welding," T. T. Heaton, Proc. Inst. Mech. Engrs., 1917-18.

TABLE CLVII.

RESULTS OF TESTS* CARRIED OUT ON SAMPLES OF MILD STEEL WELDED ELECTRICALLY BY THE "QUAZARC" PROCESS. (Tensile strength of steel 26 to 28 tons per square inch.)

No. of Sample.	*Description of Joint in Test-Piece.*	*Dimensions of Section in Inches.*	*Area, Square Inch.*	*Tons on Square Inch.*	*Elongation per Cent. in 8 Inches.*	*Nature of Test.*	*Remarks.*	*Diagram.*
A 1	Butt weld	2× 0·5	1	25	6·5	Tensile	Clean fracture through weld.	
A 2	Ditto	2× 0·5	1	22	3	,,	Ditto.	
A 3	Ditto	2× 0·5	1	—	—	Bending	Bent through 115 degrees over a radius of $\frac{5}{8}$ inch, broke through weld.	
A 4	Ditto	2× 0·5	1	—	—	,,	Bent through 180 degrees over a radius of $1\frac{7}{8}$ inches without fracture.	
B 1	Plates overlapped $\frac{1}{8}$ inch, and welded on each side	2× 0·5	1	17·2	5	Tensile	Clean fracture at weld.	
B 2		2× 0·5	1	21·8	7	,,	Ditto.	
B 3	Ditto	2× 0·5	1	—	—	Bending	Bent through 57 degrees over $\frac{3}{4}$ inch radius without fracture.	
B 4	Ditto	2× 0·5	1	—	—	,,	Bent through 180 degrees over $2\frac{1}{4}$ inches radius without fracture.	
C 1	Flat bar welded on, and then machined off before testing sample	2× 0·5	1	25·5	22·5	Tensile	Fractured outside the locality where flat bar was welded on.	
C 2		2× 0·5	1	24·5	23	,,	Ditto.	
C 3		2× 0·5	1	—	—	Bending	Bent double between welds over $\frac{5}{8}$ inch radius without fracture.	

C 4	Ditto	2× 0·5	1	—	—	Bending	Bent double at weld over $\frac{5}{8}$ inch radius, very slight fracture showing at part where flat bar had been welded.	See above
D 1	Longitudinal butt weld	2× 0·4	0·8	28·2	18	Tensile	Clean fracture across weld.	
D 2	Ditto	2× 0·42	0·84	29·2	21	,,	Very minute signs of fracture along whole length of weld.	
D 3	Ditto	2× 0·4	0·8	—	—	Bending	Bent double over $1\frac{1}{2}$ inches radius, slight fracture at welded part.	
H 1	Two 7 × $\frac{7}{8}$ inch bars welded together to form angle	—	—	—	—	Bending	Points of angle closed in, no fracture.	
H 2		—	—	—	—	,,	Points of angle opened out, fracture at weld commencing.	
H 3	Ditto	—	—	—	—	Not tested		
F 1	Flanged plate welded to angle-bar at heel and toe	4·5× 0·5	—	Breaking stress 43	4	Tensile	Clean fracture along weld.	
F 3		4·5× 0·5	—	39	3	,,	Ditto.	
F 5	Flanged plate riveted to angle-bar	$5\frac{1}{4}$× 0·5	—	18·5	—	,,	Three $\frac{3}{4}$ inch countersunk rivets, rivets pulled through holes.	
K	Plates lapped and single-riveted, one seam welded	—	—	—	—	Bending	Bent through 35 degrees at joint, no fracture at weld.	

* *Engineering*, July 10, 1914.

Applications of Oxy-Acetylene Welding.

This process is widely employed in aeronautical workshops for building up sheet metal clips, sockets, frames and lugs, engine plates, tanks, and similar parts which are not subjected to appreciable stresses. The plant cost is much lower than in the case of electrical welding, and it may readily be made portable. In automobile work the process is used for sheet metal work, body-panelling, and small unimportant fittings; it is not as a rule employed for important parts carrying loads or subjected to road shocks, as experience has shown that, unless carefully performed, and by skilled operators, such welds soon break under road conditions.

The principal application of the process, however, is in connexion with automobile repair work, and several firms now make a speciality of this class of work. The author has had some excellent repairs made to motor-car cylinders, the water-jackets of which were cracked through the water having frozen, to aluminium crank cases, magneto cases, and cylinder holding-down flanges.

In the case of repairs to water-jackets, it is often necessary to cut out a patch from the outer jacket in order to get at the inner portion, and to reweld the patch afterwards. The whole cylinder is preheated to 500° to 600° C. before welding, to avoid local cooling stresses. Cast iron and aluminium parts can be now satisfactorily welded, with suitable fluxes and precautions, and repairs may be effected to broken or cracked castings; in most cases these parts are not subjected to heavy loads, and a slight loss in strength does not matter very much.

The rims and frames of cars and bicycles are often welded by the acetylene process, and the spot or butt welding methods have been applied to replace hand-riveting processes in framework.

Many parts which have been worn down by friction can often be built up again with iron or mild steel, and afterwards case-hardened.

New teeth have also been successfully welded in gear-wheels;

it is probable, however, that the copper fusion method of fixing hard tool steel into soft steel tool-holders could also be applied to the case of broken gear-wheel teeth.

An interesting welding machine known as the "Oxygraph" is now employed for cutting out sheet metal to any pattern. The pantograph principle is employed, in which a pointer follows the original drawing or design, whilst the acetylene flame, or torch, is steered along by means of a tractor wheel driven by a small electric motor at a uniform rate. Designs can be cut with any irregularity of shape and to any scale at a rate of from 6 to 10 inches a minute in steel up to 2 inches thick, and the smoothness of the cut gives a good edge finish.

Another machine, known as the "Duagraph," is designed to weld the longitudinal seams in steel barrels and similar work. The sheet metal is bent around into cylindrical form and welded; then the bilge is made by various methods of rolling and expanding by hydraulic pressure, or alternatively two beads are rolled out. It will be seen that a very good quality of weld is necessary in order to withstand this treatment. The machine in question is so designed that there is an acetylene flame upon each side of the metal, one of which travels a little ahead of the other, so as to heat the metal in front. Welds made in this manner are very efficient.

A large amount of steel tubing is now made by seam welding rolled sheet metal, and subsequently drawing the welded tube down in dies; with suitable precautions very strong tubing can thus be made.

Welding Cast Iron.

In welding cast iron, precautions must be taken to eliminate the oxide of iron slag formed by means of a suitable flux, and to preheat the work to a dull red heat before welding, so as to avoid temperature cracks.

The oxide of iron formed is of a lighter density than the molten cast iron, and it does not melt at so low a temperature, so that with a suitable flux it can be eliminated more readily on rising to the surface of the melted metal.

In all cast iron welding work, the feeding rod, or strip, should be of ferro-silicon; this acts as a deoxidizer, and prevents the decarburization of the cast iron into white iron.

Grey cast iron is more easy to weld than white cast iron, and the production of grey iron in the welded zone is more feasible and desirable in the case of acetylene welding; there is, however, a tendency to form the white variety of iron, owing to the "burning" of part of the free graphitic carbon.

The silicon in the feeder rod combines more readily with iron than carbon does, and therefore tends to replace the latter which would otherwise combine with the molten iron; moreover, it even displaces carbon already combined with iron, setting it free to replace that previously "burnt" out during welding. A suitable flux* consists of equal parts of soda bicarbonate and soda carbonate, to which may be added about 12 per cent. of borax and 5 per cent of precipitated silica.

The presence of manganese in cast iron or in the feeder rod tends to promote the formation of white iron, by oxidizing the free carbon, and it should therefore be present only in very small quantities.

It is important not only to slowly heat the parts before welding, but also to allow them to cool down slowly after welding.

Nickel-iron alloy rods† for the electric resistance method of welding are stated to give consistently reliable results in connexion with the welding of cast iron.

Welding of High Carbon Steel.

It is only possible to properly weld steels containing below about 1·25 per cent. of carbon, and in these cases the same procedure is adopted as in the case of cast iron, but steel wire or rod is used for feeding.

Welding Malleable Iron.

Malleable iron is welded in the same manner as cast iron except that the feeder employed is one of Swedish or charcoal iron; it is necessary, also, to preheat the work.

* Recommended by The British Oxygen Co., Ltd.

† Alloy Welding Processes, Ltd., London.

Welding Copper and its Alloys.*

The principal difficulties experienced in the welding copper are due to the great heat conductivity of the met which necessitates a higher flame temperature or a larger blo pipe, and to the property which copper possesses of rapid oxidizing, and of dissolving its own oxide when molte Further, the effect of the well-known property of molten copp for occluding gases such as oxygen, carbon-monoxide, ai hydrogen, is to render the metal porous when cool, owing the escape of these gases.

It has been found that if phosphorus is used as a flux, or incorporated in the welding rod, the absorption of gases prevented and the oxidation of the molten metal does n occur, owing to the formation of phosphoric acid, by the oxyg and the phosphorus, which floats on the surface of the molt metal and forms a protective layer.

The welding of copper alloys such as gun-metal, brasses, ai bronzes necessitates the careful selection of a suitable weldi rod, for the constitution of these alloys varies considerabl and certain of the elements present, such as lead, zinc, nick may become oxidized. For most common purposes a weldi rod of rolled manganese bronze has been found suitable; ai it is advantageous to have a small percentage of phosphor and also of zinc present in the composition, to replace tl oxidized or volatilized metal. The best all-round flux is bora Care should be taken not to overheat the metal, the mo suitable temperature being the one at which small globul appear upon the prepared surfaces.

Welding of Aluminium.

It is now possible to weld aluminium, although the proce is by no means an easy one; many aluminium fuel tanks f aircraft, containers, sheet-metal and panel work, casting domestic utensils, etc., are now satisfactorily welded.

The chief difficulty experienced in the process of weldi

* The following procedure is that recommended by the British Oxyg Co.

is to eliminate the oxide formed at the surfaces of the molten metal; this oxide has a higher melting point than that of the metal itself, and it forms very readily, for aluminium, when molten, has a great affinity for oxygen.

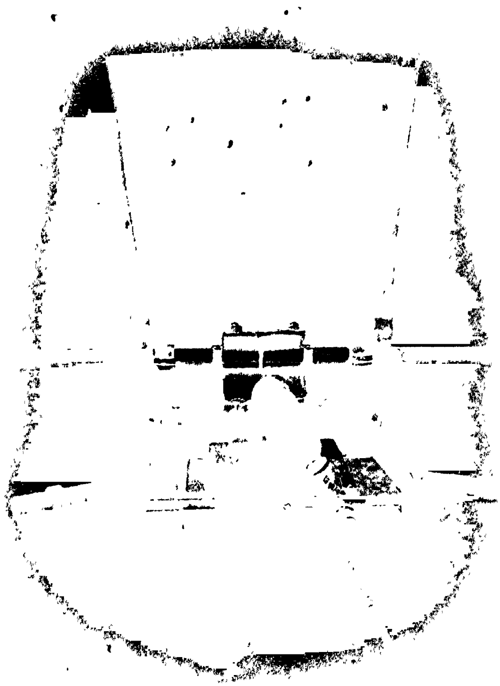


FIG. 270.—BUTT WELDING MACHINE FOR ALUMINIUM, ETC.

The presence of this oxide film not only affects the heating properties of the flame on the joint, but if it is not eliminated it solidifies before the other metal and forms a skin, or coating, over the joint, so that no junction is made.

The melting point of the oxide is nearly 3000° C., whereas that of the metal itself is only 650° C., so that the difficulty in providing a suitable flux, which will dissolve the oxide at

the low melting point of the metal, and at the same time protect the molten metal against further oxidation, is by no means a small one.

Fluxes of special composition are now available, and these are found to give satisfactory results.

It is an advantage to tap or slightly hammer the joints after welding, and to reheat to about 450° C. In welding aluminium sheets, the surfaces must be well cleaned and butted together. The flux is applied in the form of a paste, and when the blowpipe flame is applied and worked along the seam the metals will unite and the oxide, or slag, will float to the surface.

In *butt welding*, the oxide and a small quantity of the metal are mechanically squeezed out of the joint, from which they are afterwards removed upon cooling down. Fig. 270 illustrates a typical butt-welding machine.*

In *cast welding* the oxide flows to the top of properly designed risers in the mould itself.

Oxy-Acetylene Metal Cutting.

The oxy-acetylene, coal gas, hydrogen, or benzol vapour flame can be made to sever, or to cut through steel plate of almost any thickness, with almost the rapidity of hot-sawing, and with similar results as regards the appearance of the cut edges; it possesses the further advantage, however, of being able to cut out any shape or profile.

The principle of the cutting of metal by an oxygen-gas flame consists in first melting the metal, next combusting or oxidizing it, and then rendering the oxide formed molten, afterwards blowing it away with the oxygen or a separate oxygen supply.

Oxide of iron is formed at a fairly low temperature, but it is not very fluid, so that unless it can be eliminated from the heated area it adheres to same, and not only acts as a heat insulator, but also prevents further combustion.

Special metal cutting blowpipes are now employed, in which an additional or third passage is provided for an independent supply of oxygen for furnishing the additional heat necessary

* The British Aluminium Co., Ltd., London.

to keep the oxide fluid, but also to blow it away from the metal.

Fig. 271 illustrates a metal-cutting blowpipe, made by the British Oxygen Co., in which the combustible gas (that is, the acetylene and oxygen in their correct proportions for com-

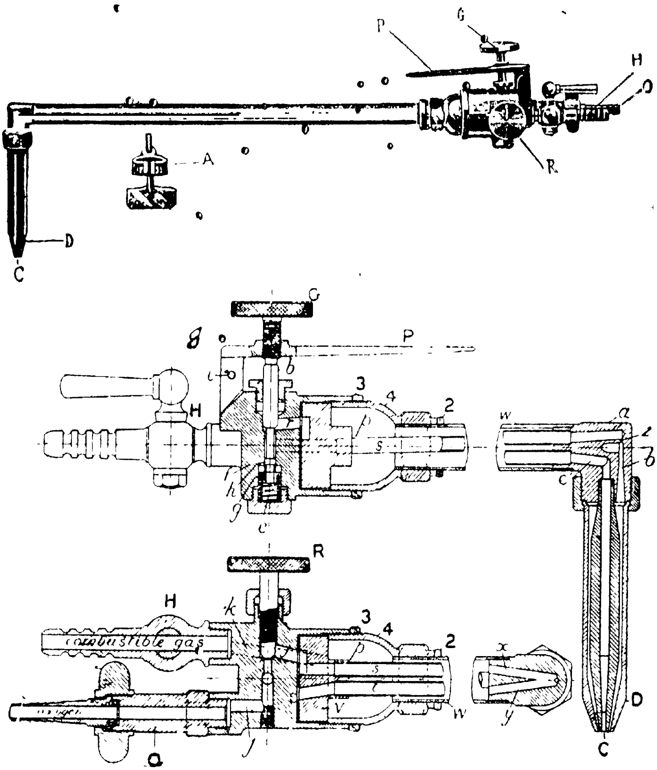


FIG. 271.—METAL CUTTING BLOWPIPE.

bustion) is led into the annular space D, whilst the independent oxygen supply is conducted through the central passage C. Regulators are provided at G, P, and R for varying the quantities of the oxygen and combustible gas.

In the case of metal-cutting machines, which are designed to feed the blowpipe or metal relatively to each other at a given

rate, the blowpipe usually has a separate oxygen supply pipe which is brought to a passage immediately behind the heating flame.

When acetylene gas is employed it is found that for thick plates of 1 inch and over the oxygen and acetylene proportions are about 9 to 1, whilst for the thinnest plates they are about 3 to 1.

With coal gas the corresponding proportions are roughly 4 to 1 and 1 to 1 respectively; this gas is more suitable for small work and thin plates, owing to the lower temperatures concerned, and for plates up to about $\frac{3}{4}$ inch the coal-gas system gives cleaner but slower results.

Metal plates up to nearly 2 feet in thickness can be cut by these methods; armour plate is readily cut to any shape; patches can be cut out of ships, plates, and bars; rods and parts of almost any section can be readily severed.

Table CLVIII, on p. 632, gives some idea of the rates of cutting mild steel plate, together with the oxygen pressures and consumptions.

Thermit Welding.

This method possesses the advantage that it can be applied in a very compact and portable form It consists in heating a mixture of powdered aluminium and iron-oxide, such as mill scale, with a special igniter powder, in a small fire-brick lined funnel-shaped vessel; when the combustion, or rather the ignition point is attained the aluminium combines with the oxygen of the iron-oxide, setting free the iron, and the temperature of the reaction is about 3000° C. The iron is produced in the molten state, covered with a slag, and it can then be "tapped" into the joint to be welded. So intense is the heat evolved, that if a 1 inch steel plate is placed under the tapping hole a clean hole will be burnt right through it immediately.

In many cases wrought iron or steel turnings, punchings or shearings, are mixed with the thermit powder in order to give a stronger metal.

It is estimated that about 6 or 7 pounds weight of thermit is required for every square inch section of the joint to be

TABLE CLVIII.

CUTTING RATES, PRESSURES, AND GAS CONSUMPTIONS FOR MILD STEEL PLATE. (B. O. Co.)

Thickness of Plate, Inches.	*Oxygen Pressure at Regulator Outlet, Pounds per Square Inch.*	*Oxygen Consumption per Hour in Cubic Feet.*	*Foot Run of Metal Cut per Hour.*	*Oxygen used per Foot Run of Cut.*
$\frac{1}{4}$	24	48	65	$\frac{3}{4}$
$\frac{1}{2}$	28	60	60	1
$\frac{3}{4}$	32	75	50	$1\frac{1}{2}$
1	32	88	40	$2\frac{1}{2}$
$1\frac{1}{4}$	36	95	35	$2\frac{3}{4}$
$1\frac{1}{2}$	39	105	30	$3\frac{1}{2}$
2	45	125	25	5
3	52	180	20	9
4	58	300	20	15
5	65	420	20	21
6	70	432	18	24
8	80	504	18	28
11	115	620	13	48
12	125	650	13	50
14	125	900	12	75
17	130	1350	12	112

Note.—The size of the cutting nozzle varies from $\frac{1}{32}$ inch for $\frac{1}{4}$ inch plate up to $\frac{7}{64}$ inch for 12 inch plate, but a wide range of thicknesses may be cut with each nozzle by simply varying the amounts of gas passing through.

welded; the weight of a cubic inch of thermit is about 0·28 pound.

This process is very convenient for open-air repairs to such parts as railway lines, tramway rails, tyres, ship's repairs, and similar purposes.

It is important to avoid all traces of moisture in the powder or upon the faces to be welded, otherwise blow-holes may be caused.

The strength of a properly executed thermit weld is believed to be somewhat better than that of electrical welds on account of the greater volume of heat and of the absence of oxides.

The Union of Metals by Compression.

It is well known that when metallic powders are subjected to high pressures in a mould, they will unite into a

solid mass, which possesses all of the properties of the original metal from which the powder was obtained.

When lead particles or filings are compressed in a cylindrical mould at a pressure of 13 tons per square inch, they become compressed into a solid block, whilst at about 33 tons per square inch pressure the lead flows like a liquid through all the cracks of the apparatus.

Lead pipes and other shapes may be extruded or squirted in this manner, and copper locking-washers and rings between iron or steel male and female members can also be squirted similarly.

Bismuth, which is a hard, brittle, crystalline metal, when in the form of powder, unites under a pressure of about 38 tons per square inch into a hard mass similar to that obtained by fusion, and which gives the same crystalline fracture.

Different metals require different union-pressures as the following results show:

Lead unites at	13 tons per square inch.
Tin ,, ...	19 ,, ,,
Zinc ,, ...	38 ,, ,,
Antimony unites at	38 ,, ,,
Aluminium ,, ...	38 ,, ,,
Bismuth ,, ...	38 ,, ,,
Copper ,, ...	33 ,, ,,
Lead flows at	33 ,, ,,
Tin ,, ...	47 ,, ,,

It has also been shown that certain alloys can be produced by subjecting a mixed powder of the constituents to high pressure. Thus, if a mixture of finely divided metals consisting of bismuth 15 parts, lead 8 parts, tin 4 parts, cadmium 3 parts, be compressed, the well-known alloy, fusing at 100° C., is obtained. The melting point of the most fusible of the constituents--namely, *tin*—is 232° C.

The manufacture of compound sheets of different metals, such as nickel and steel, copper and steel, aluminium and copper, etc., is also based upon the above principle, but heat is applied to facilitate the process.

In the manufacture of copper-aluminium sheets, the copper sheet is first pickled, cleaned, and dried. Aluminium powder is then brushed on by machinery, or by means of brushes.

A sheet of clean aluminium is then placed on the copper, and the two are heated and passed through the rolls. The union thus obtained is perfect, and the compound sheet can be worked, machined, stamped or spun as a solid sheet.

There are, of course, other electrolytic and chemical or fusion methods for making compound sheets; these are, however, somewhat outside the scope of the present work.

CHAPTER XII

THE PROTECTION OF METAL SURFACES

THE question of the protection of metal surfaces exposed for long periods to corrosive influences is an important one, more especially in aeronautical work, since in many cases it affects the strength and durability.

Thin plates and tubes, tension wires, seaplane and flying-boat fittings, the individual wires of cables, soldered and welded joints, etc., are very apt to rust, and in cases where the thickness of the part is small, the effects of corrosion may be serious.

Corrosion of Iron and Steel: Theoretical Considerations.

Primarily corrosion consists in the oxidation of the iron itself, due to the combined influence of the oxygen and carbonic acid gas of the air, and of moisture. The results of investigation show that iron cannot rust in air or in oxygen, unless there is some water present, and that it cannot rust in water unless oxygen is present.

The chemical composition of iron rust is a complex one, and it has been shown* to consist of hydrated oxides of iron, basic ferric carbonate, organic matter, and very often fixed sulphur; phosphates and silicates are also present.

Many theories have been advanced to account for the corrosive action effects, amongst which the electrolytic theory is, perhaps, the most convincing. This theory assumes that it is necessary for iron to first pass into solution as a ferrous iron before it can oxidize in the wet way. During the process of solution the iron becomes electrically charged, and the dissolved portion receives an equal and opposite charge. Solu-

* "Corrosion and Rusting of Iron," E. K. Rideal, Proc. Soc. of Engrs., 1917.

tion ceases when the electrical balance is attained, unless there is some other mechanism whereby this balance is prevented. It is thought that the formation of numerous minute electrolytic cells all over the metallic surface is one of these preventative influences which causes solution to continue.

The hydrogen which is liberated at the surface of the iron should, in the ordinary way, act as an insulating medium and prevent further action; but, unfortunately, it does not do this, for it combines with the atmospheric oxygen and leaves the metal surface unprotected. It is generally believed that the rate of corrosion is governed by the rate of combination of the oxygen and hydrogen, unless there is another depolarizer present.

It is apparent from the above theoretical considerations that in order for a metal to possess the highest non-corrosive tendencies, it should be as free as possible from certain impurities, such as manganese, and that it should be so homogeneous as not to retain localized positive and negative nodes for long periods.

Some Practical Considerations.

It has been shown, more or less conclusively, that iron does not corrode so rapidly as steel; for example, in one series of tests* pieces of iron plate and soft Bessemer steel were both cleaned and polished, and were exposed to the action of a mixture of loam and sand, with which had been thoroughly incorporated some carbonate of soda, nitrate of soda, ammonium chloride, and magnesium chloride, with moisture. The pieces of metal were taken out, cleaned, and weighed after 33 days' action, when the iron was found to have lost 0·84 per cent., and the steel 0·72 per cent. of its weight. Tests, lasting over a period of seven years, also showed that the average corrosion of mild steel was about 120 per cent. greater than that of wrought iron.

It is also known that iron or steel which is subjected to vibration rusts less quickly than otherwise; for example, steel rails which are not in use rust quicker than those in actual use.

* Tests made at Riverside Iron Works, Wheeling, W. Va. (Kent.)

One point in connexion with the corrosion of iron, which does not appear to have received the attention which it merits, is that very fine-grained hard surfaces, such as those of case-hardened or hardened iron and steel, rust far less quickly than those of the untreated material.

Large open-grained metal, such as wrought and cast iron, is found to corrode fairly rapidly; cast iron in salt water becomes soft and porous, so that in some cases it can be cut with a knife. White, close-grained cast iron is found to be less affected by corrosion than the coarser-grained grey variety.

The following table shows the relative corrosion of mild and nickel steels, compared with wrought iron, under the respective influences of fresh and salt water and the weather:

TABLE CLIX.

RELATIVE CORROSIONS OF STEELS AND IRON. (H. M. HOWE.)

Metal.	*Sea Water.*	*Fresh Water.*	*Weather.*	*Average.*
Wrought iron	100	100	100	100
Mild steel	114	94	103	103
3 per cent. nickel steel . .	83	80	67	77
26 per cent. nickel steel . .	32	32	30	31

The following values* relate to the relative corrosions of rolled bars of Delta IV. metal, wrought iron, and steel, each of which measured 7·5 inches long, and had a sectional area of 0·62 square inch, and which were exposed for 6½ months in pit water:

TABLE CLX.

RELATIVE CORROSIONS OF METALS IN PIT WATER.

Metal.	*Weight of Bar when first put into Water.*	*Weight after 6½ Months.*	*Percentage Loss in Weight after 6½ Months.*
	Pounds.	*Pounds.*	
Wrought iron . .	1·1805	0·6393	46·3
Delta metal . .	1·2787	1·2633	1·2
Steel	1·2125	0·6614	45·45

* The *Engineer.*

Manganese bronze, when immersed in colliery water, noted for its bad rusting properties, was found to have lost about 20 per cent. of its weight after 52 days' immersion, and Delta metal 4·43 per cent.

It has also been found that the acids and other constituents of timbers, such as oak, cause corrosion of iron or steel objects in contact with them.

For this reason it is usual to employ copper, aluminium, or copper alloys, such as the bronzes and Delta metals, for fittings directly attached to timber.

Copper bolts and rivets are much used in shipbuilding and structural work partly for this reason.

There are now certain alloy steels, such as the 25 per cent. nickel steel and high chrome or "stainless" steel, which are practically non-corrodible, whilst certain of the aluminium and copper alloys will withstand exposure for long periods without experiencing corrosion.

It has been shown that corrosion is greatly accelerated by the increase in the sulphurous acid in the air of manufacturing towns, and by the presence of strong electric currents in the ground of towns.

For these reasons, ordinary lead pigment paints are not satisfactory, and more effective measures must be adopted.

Mill-black (Fe_3O_4) has been found to be electro-negative to the metal itself, and therefore to act as a stimulator of corrosion under certain circumstances.

Linseed oil, which is frequently employed for paints and coatings, is an unsaturated hydrocarbon, and acts under certain conditions as a depolarizer, so that it accelerates corrosion in these cases.

Corrosion Prevention Measures.

Apart from the prevention of rusting or corrosion by keeping the metals thoroughly dry—a procedure which can seldom be realized in practice—there are four principal methods of protecting metallic surfaces which are exposed to corrosive influences—namely:

(a) The process known as "browning" or "blueing" of polished steel articles which is, to a certain extent, a protective measure, the film of oxide formed protecting the metal.

(b) By coating with a varnish or lacquer.

(c) By painting with oxides, non-corrosive paints, and solutions.

(d) By the deposition of a non-oxydizable or electropositive metal upon the surfaces.

(a) Browning Methods.

The commonest mode of "browning" consists in heating the polished parts in a sandbath to a temperature of about 250° to 260° C., and allowing to cool.

Another method consists in heating to about 300° C. or above, and plunging the part into oil; to obtain a thicker coating the part, when covered with mineral oil, is heated in a muffle or furnace until the oil is just burnt off and then plunged into oil again.

Other methods of browning employ special chemical solutions, and properly come under the heading of paints.

In a number of the heating processes to be described, it is not possible to efficiently treat hardened and case-hardened steels, so that the adoption of cold-metal processes and paints is necessary in these instances, in order that the proper degree of strength and temper may be retained.

(b) Varnishes and Lacquers.

The method (b) possesses the advantage that as the varnish or lacquer is usually transparent, the condition of the surface can be readily examined; it is employed for small parts which do not require to be handled very often. A good lacquer should be hard and elastic, but should not chip or peel off, and should be capable of withstanding ordinary atmospheric temperature effects. These lacquers are often applied in the heated state to the metal surfaces.

The following are a few typical protective varnishes and lacquers for iron and steel: *

* For fuller information reference should be made to Spon's "Workshop Recipes," Kempe's "Year Book," and similar works.

Lacquers.

These are generally employed for brass and aluminium work, but the process of lacquering is more easy to apply to small than to large articles.

Lacquer derives its name from one of its constituents—namely, shellac or seed lac, which is derived from the gums or resins of trees exuded by the lac insect.*

Shellac, or purified seed lac, in the form of thin sheets, is a constituent of most lacquers, and when bleached it forms a colourless compound which is frequently employed in transparent varnishes and lacquers; alcohol or spirits of wine is used as a solvent for most resins and gums.

It is necessary to thoroughly clean the articles beforehand, and to heat them to about 100° C., taking care that there are no oxydizing influences nor grease or oil present, during heating.

Brass Lacquers.

Ordinary lacquer consists of shellac dissolved in alcohol (methylated spirits), roughly in the proportions of half a pound of shellac to one gallon of the spirit. The clear portion of the spirit is canted off and filtered, when it is ready for use; the addition of resins and other ingredients is made in order to improve the quality of the resulting lacquer. The following are typical lacquers for brass:

(*A*)	Shellac	8 ounces	The article to be lacquered should be slightly heated and the lacquer applied with a camel-hair brush.
	Sandarac	2 „	
	Annatto	2 „	
	Dragon's blood resin	¼ ounce	
	Spirits of wine	1 gallon	

(*B*) *For Instrument Lacquering* :†

Seed lacquer	6 ounces.
Dragon's blood	40 grammes.
Amber and copal (powdered)	2 ounces.
Red sanders extract	½ drachm.
Oriental saffron	36 grammes.
Coarsely powdered glass	4 ounces.
Absolute alcohol	40 ounces.

* "The Lac Industry," *Journ. of Roy. Soc. Arts*, August 16, 1919.

† Spon.

Iron and Steel Lacquers.

These lacquers may be either transparent, coloured, or black, and are usually made by the addition of asphaltum and similar substances to alcohol-shellac solutions, or to solvents such as benzine or carbon-disulphide.

Coal-tar products also form the base of metal-protecting lacquers. The following are typical lacquers:

(*A*)	Asphaltum	3 pounds.
	Shellac	½ pound.
	Turpentine	1 gallon.
(*B*)	Spirit black	12 ounces.
	Methylated spirit	1 gallon.
	Sandarac	1 ounce.
	Button shellac	3 ounces.
(*C*)	Camphor	1 ounce.
	Sandarac	3 ounces.
	Mastic	2 ounces.
	Elemi (dissolved in spirits of wine) ..	1 ounce.

(*D*) A good lacquer for protecting nickel-plated fittings and brass parts upon automobiles may be made by dissolving ordinary celluloid in amyl-acetate until it has the consistency of a thin syrup. It should be kept in an air-tight tin, and when required for use should be applied with a camel-hair brush.

(*E*) Dissolve white wax in benzine and apply with a brush. This method gives a fine wax surface, which will not, however, withstand much handling.

Many of the metal protecting paints and so-called varnishes should properly come under the heading of lacquers.

Varnishes for Metals,* etc.

Most varnishes consist of solutions of resins or gums in oil, turpentine, or alcohol; when the varnish is applied to a surface exposed to the air, the spirit evaporates and leaves the hardened oil, gum, or resin as a thin coating of uniform texture.

Varnishes for metal work are mostly of the polished variety, and it is essential that they should give a hard, tough, and dur-

* The following remarks also apply generally to the case of wood and similar varnishes.

able surface; the quality of a varnish will depend upon its ingredients, and upon the processes of mixing and applying it to the surface to be coated.

The principal ingredient in varnishes are the resins,* or gum-resins, and it is upon the quality of the resin employed that the value of the varnish largely depends.

The commonest resin employed is the ordinary *rosin* or *colophony*, which is obtained by distillation from spruce turpentine or from Bordeaux turpentine. Amongst the resins employed for varnishes may be mentioned the following—namely:

(1) *Amber*.—A fossilized resin which is found upon seashores after heavy storms, and in fossiliferous deposits; it is one of the best resins for varnishes, being very hard, tough, and durable. It is hard to dissolve, and when in a varnish dries very slowly; it is one of the ingredients of the more expensive varnishes.

(2) *Copal*.—A resin, imported from the tropics; it is used in three qualities, and graded according to its colour, the palest being the best.

(3) *Gum Animé*.—A hard resin, difficult to dissolve in alcohol, which is very hard and durable. It tends to darken in colour and to crack when used alone in varnish.

(4) *Dragon's Blood*.—This is a dark red resin, which is used for varnishes and for colouring varnishes. It is sold in powder or lump form.

(5) *Sandarac*.—A resin derived from the juniper tree; it is light in colour and rather soft.

Other resinous substances employed include *gum dammar*, *gum elemi*, and *lac*.

These resins each require suitable solvents; for example, alcohol or spirits of wine is used for shellac, lac, and sandarac; turpentine for mastic, gum dammar, and ordinary resin; and boiled linseed oil for amber, gum animé, and copal.

The nature of the solvent also determines the class of the varnish; thus an *oil varnish* is one in which the gums or resins are dissolved in oil, a *spirit varnish* one in which alcohol is

* The so-called "gums" are soluble in water, and should not, therefore, be used for varnishes of exposed parts.

the solvent, and *water varnish* one in which the gum is dissolved in water.

Oil varnishes are the hardest and most durable, but require a much longer time in which to dry;* they are usually made from the hardest gums, such as amber, copal, and gum animé dissolved in linseed, poppy and other oils.

A typical oil varnish, suitable for protective purposes, and for coach- and motor-body work is as follows:

Best African copal	8 pounds.
Clarified oil	2 gallons.
Turpentine	3½ gallons.

The first two ingredients are boiled together slowly for three or four hours until quite stringy, and are then mixed with the turpentine.

Another oil varnish suitable for protecting metals and timbers against atmospheric influences is as follows:

Powdered resin	6 pounds.
Turpentine	5 pints.
Boiled linseed oil	1¼ gallons.

The first two ingredients are dissolved, and the oil is added afterwards.

Spirit varnishes are usually made from the softer gums and resins, such as sandarac and lac (or shellac), dissolved in alcohol (or spirits of wine). These varnishes or lacquers give a hard and brilliant polish, and dry much more readily than the preceding ones, but are not so durable and are apt to crack and peel off; they are chiefly used for timbers.

The following are typical spirit varnish compositions:

(*A*) *Copal Spirit Varnish :*

Copal gum	8 parts.
Balsum capivi	2 ,,
Turpentine	10 ,,

The two former ingredients are melted first and then added to the warmed turpentine.

(*B*)

Gum sandarac	7 pounds.
Spirits of wine	2 gallons.
Turpentine	1 quart.

This is a hard white varnish.

* A good coach varnish usually requires from 1½ to 3 days to dry properly.

(*C*) *Asphalte Varnish for Iron and Steel:*

Tar oil	2 pounds.
Asphaltum	½ pound.
Powdered resin	½ pound.

These ingredients should be melted in an iron vessel and thoroughly mixed by heating.

(*D*) A good protective varnish for preserving polished surfaces is obtained by adding a little olive oil to melted resin in a pot, and then, after removing the pot, adding a small quantity of turpentine. With a little experience in apportioning the constituents, a fine, hard, elastic coating can be obtained.

(*E*) Another excellent anti-rust varnish is made by powdering and digesting at a uniform heat the ingredients below, and then adding turpentine to the melted mass. Finally, after the whole has formed a proper solution, rectified alcohol (180 parts) is added; the final solution is then filtered through paper or fine cloth and is ready for use. The following are the proportions of the constituents:

Resin	120 parts.
Sandarac	180 ,,
Gum lacquer	60 ,,
Essence of turpentine	120 ,,
Rectified alcohol	180 ,,

[For other recipes the reader is referred to Spon's "Workshop Recipes," volume iv. (E. and F. Spon, Ltd., London).]

Protective Paints and Coatings.

One of the commonest, and, at the same time, most economical metal protective methods, consists in painting the surface with a coating of suitable ingredients.*

It is, of course, of primary importance to select only those materials which do not chemically affect the metallic surfaces.

An efficient metal protecting paint or covering of any kind should possess the following characteristics—namely:

(1) It should be quite water and acid proof.

* Enamels consisting of suitable pigments, and dryers with varnish as the vehicle are also classed under this heading. The process of stove-enamelling consists in heating the enamelled parts, whilst still wet, for a period varying from 12 to 48 hours in a constant temperature warm oven. A hard and brilliant surface results, which is an excellent corrosion preventer.

(2) It should be chemically stable.

(3) It must have about the same coefficient of expansion as that of the metal itself, to avoid cracking and crinkling.

(4) It must be impervious to extreme atmospheric heat influences.

(5) The surface should be hard, tough, and elastic, and thoroughly in contact with the metal itself.

(6) It should withstand vibration and a reasonable amount of friction and abrasion.

(7) It should preferably be a non-conductor of electricity, and should be free from depolarizing constituents such as unsaturated hydrocarbons and linseed oil.

(8) It should give a good covering surface, and be cheap and convenient to use.

One of the commonest of protective coatings consists of a mixture of oxide of iron (known as "red lead") and linseed oil; it is used as a primary coating for steel and iron plate.

Linseed oil is one of the principal ingredients of most of the preserving paints, and the pigments consist of white lead (carbonate or oxy-sulphate), white zinc (oxide), red lead, graphite, lamp-black, and various coloured pigments for tinted paints.

It is necessary to include in the composition of paints certain substances such as litharge, sugar of lead, or white copperas, to act as *driers*.

The addition of a suitable pigment to an oil paint increases the efficiency of the latter as a metal protective paint up to a certain maximum, after which the further addition of pigment has a detrimental effect; it is essential to employ a good oil such as boiled or polymerized linseed oil.

The pigment toughens the resulting film and renders it less permeable to water, oxygen, and other corrosive influences; it also reduces the expansion of the oil on setting, and therefore minimizes the "crinkling" tendency which is primarily due to the expansion (about 3·3 per cent.) of the linseed oil on cooling.

It is stated* that the most permanent paints are those containing black or red pigments, since these absorb the shorter

* "Paint for Iron," by Dr. J. Newton Friend, *Journ. of Iron and Steel Inst.*, 1918.

rays of light and prevent them from accelerating the destructive oxidation of the linoxyn by the air. Finer pigments are more efficient than coarser ones owing to their being in more intimate contact with the oil.

When protective paints or coatings are applied,* it is better to obtain the necessary minimum thickness for protection, by giving several thin coats in preference to one or more thick coats. It is also considered desirable to paint steel plates with the hard "rolling scale" still on, since this scale, or black iron oxide (Fe_3O_4), is, in itself, a protection; these remarks do not, of course, refer to the loose, easily detachable scale.

There is a large number of metal primers or paints upon the market, many of which give satisfactory results. The basis of many of these paints consists of a tar or hydrocarbon oil.

Tar Oil Preservatives.

An efficient rust preventer for iron and steel consists of a liquid made up of equal parts of tar oil and hydrocarbon oil; this should be applied to the cleaned and heated surface of the metal.

Another good preservative consists of coal tar which has been boiled to expel the moisture and naphtha, and which, when cold, is mixed with naphtha in the proportions of about 16 parts of the oil to one of naphtha.

Rust-Proof Coatings for Steel.

(*A*) The following is the composition† of an efficient preservative coating:

Calcium resinate	36 parts.
Manganese borate	½ part.
Lead acetate	1 ,,
Artificial graphite	25 parts.
Naphtha	37½ ,,
Linseed oil	25 ,,

These ingredients are well mixed and are applied to the surface to be coated by means of a brush, or by dipping. The surface is then heated to 300° F. in an oven for about two hours. The surface obtained is a polished one.

* Modern methods of painting articles, motor-car bodies, etc., are described in Vol. II. of this work.

† *American Machinist.*

(*B*) A method often adopted for protecting new machinery and stored parts is to smear, or apply warm with a brush, a mixture composed of 1 ounce of camphor dissolved in 2 pounds of melted lead, to which fine plumbago or black lead is added. This mixture can be readily wiped off at any time.

(*C*) Another method consists in adding 7 ounces of quick-lime to about $1\frac{3}{4}$ pints of cold water, afterwards pouring off the supernatant liquid. Sufficient olive oil is added to the mixture to give it a cream-like consistency. The articles are greased with the resulting mixture, and may be further protected by wrapping them in soft rags.

Chrome Paints.

It has been found that if iron and steel surfaces are painted with a 5 to 10 per cent. solution of chromic acid or potassium bichromate solution, they will withstand corrosion to a remarkable extent. The process does not appear to affect the structure of the metal, and its action is not yet fully understood.

This process is not as it stands applicable to commercial purposes, but is quoted merely in order to point out the beneficial effects of chromium compounds.

It is stated* that the best paint pigments of this class are zinc chromate, American vermilion, and chrome yellow orange. The following is the composition of a chromium paint which is recommended:

American vermilion or zinc chromate ..	40 pounds.
Red lead	10 ,,
Venetian red	5 ,,
Zinc oxide and lamp-black (sufficient to produce the desired shade).	

These ingredients should be ground in $1\frac{1}{3}$ gallons of raw linseed oil, increasing the quantity as required for the added colouring pigment, and about 1 pint of drier compound should be added. This mixture should be thinned for use with raw oil and a little benzine or turpentine.

Quantity of Paint Required.

For the first coat, upon a properly cleaned surface, 1 gallon of ordinary paint will suffice for from 250 to 350 square feet,

* Dr. Cushman, Bulletin No. 30, U.S. Dept. of Agriculture, 1907.

whilst for the second and each subsequent coat it will cover about 300 to 450 square feet.

Bowranite Paint.

A very effective bituminous paint employed for rust-proofing steel and iron is known as "Bowranite";* it possesses the advantages of giving a hard, elastic, waterproof covering, which withstands the ordinary thermal expansions and contractions without crinkling or cracking, and it is practically unaffected by atmospheric influences, sea water, or sulphurous gases.

The writer has made certain tests with this covering, and has found that it is very efficient as a metal protector. It is necessary to clean the surfaces well before applying the thin black Bowranite paint, and to give two coatings; each coat dries in about three hours. About 1000 square feet superficial area can be covered with 1 gallon of this covering, so that it does not add appreciably to the weight of an article to treat it in this manner; indeed, it shows a marked improvement over the ordinary metal coating processes.

It may be of interest to quote the results of some fairly stringent tests† made upon this paint:

(1) Two steel plates were taken, one of which was coated with Bowranite to the maker's instructions, and the other was untreated. Both were simultaneously exposed for 46 days to the atmosphere and the weather; at the end of this period the uncoated plate was red with rust, and had lost one-thirtieth of its weight, whilst the coated plate was quite unaffected.

(2) Two steel plates, one coated and the other untreated, were intermittently immersed in sea water, and then exposed to atmospheric influences by arranging for them to be alternately covered and exposed by the rise and fall of the tide for a period of 4[illegible] days. At the end of this period the uncoated plate was very rusty and had lost one-third of its weight, whereas the coated one was unaffected in appearance except for a slight deposit from the water and had lost no weight.

* Manufactured by Messrs. R. Bowran and Co., Ltd., Newcastle.

† Tests made by Dr. Dunn, F.I.C.

(3) Two steel plates, one coated and one untreated, were both exposed to acid fumes in a chamber for 46 days, after which the untreated plate was nearly rotted through, whilst the coated plate was found to have lost no weight. Only a slight dulling and roughening of the surface was found to have occurred.

(4) The elasticity of the paint was tested by coating a piece of bright copper foil and bending it backwards and forwards until it broke; it was found that the coating showed no tendency to crack or peel off.

Coslettizing.—This process, which is often applied to bicycle and car frames and other similar cases, consists in boiling the steel parts for a definite period in a solution consisting of 1 ounce of iron filings and 4 ounces of phosphoric acid in each gallon of water. The surface obtained is matt-black, and it has been shown to be a very satisfactory rust preventer; it can, moreover, be stove-enamelled afterwards.

Metal Coating Processes.

Many steel, iron, brass, and other metal parts are now protected against oxidation and corrosion by giving them a coating of another non-oxidizable metal, such as zinc, copper, nickel, or aluminium; in most cases there is an intimate admixture or alloying of the two metals at the surfaces of junction.

The principle upon which the results of all zinc depositing processes is based depends upon the fact that when iron or steel and zinc are in contact and are immersed in an electrolyte, the zinc is electro-positive to the iron, and therefore the zinc will be dissolved away and the iron left practically unaffected; zinc-coated iron or steel in a moist atmosphere containing oxygen and carbon dioxide behaves in this manner, the zinc only corroding.

This is the principle of the method adopted in steam boiler practice in order to prevent the steel boiler shell and tubes from rusting in the presence of the hot water (which often contains acids). In these cases, slabs of zinc are suspended within the boiler, and these gradually disappear, the iron being protected all the time. Cast-iron pipes placed underground

for long periods are often corroded by electrolytic action, the oxides of iron mixed with the graphite usually remaining in place and presenting the same outward appearance as before, but actually having no mechanical strength and little cohesion; the presence of stray currents from electrical systems such as electric railways and tramways also greatly assists the above action. The following table shows the electrolytical order of various elements, each element being electro-positive to those following it:

TABLE CLXI.

ORDER OF ELEMENTS.

Element.	*Absolute Potential.*	*Element.*	*Absolute Potential.*
1. Manganese ..	+0·798 volt.	9. Hydrogen..	−0·277
2. Zinc ..	+0·493	10. Copper ..	−0·606
3. Cadmium ..	+0·143	11. Mercury ..	−1·030
4. Iron	+0·067	12. Silver ..	−1·048
5. Tellurium ..	+0·045	13. Chlorine ..	−1·630
6. Cobalt ..	−0·045	14. Bromine ..	−1·270
7. Nickel ..	−0·049	15. Iodine ..	−1·797
8. Lead ..	−0·126		

Note.—Elements above hydrogen, in number, pass into solution when in contact with hydrogen ions, and those below hydrogen are not attacked.

The protecting metal may be deposited electrolytically by chemical means, by the method of mechanical deposition, utilizing a fine spray of pulverized metal, or by dipping.

Small aeroplane fittings such as steel bolts, strainers, clips, sockets, and plates are frequently protected by first pickling in a weak hydrochloric acid bath, then copper plating, and finally dull nickel plating.*

The small screws, springs, clips, and similar parts used in instruments are often dull copper plated by placing them in a copper sulphate solution, in contact with an iron plate. Many of the patented processes employ zinc as the protective surface, the zinc being deposited either electrolytically, by dipping the article in molten zinc, chemically, or by metal spraying; one or two of the better-known processes will now be considered.

* For fuller particulars see "Nickel and its Alloys," Chapter IV., Vol. II., of this work.

Galvanizing.

The ordinary process of hot galvanizing consists in first cleaning the article of all scale, paint, or dirt, and then pickling it in a 5 to 8 per cent. hydrochloric acid bath for about 8 to 14 hours. It is then dried and is next dipped into a molten zinc bath at a temperature of from 400° to 500° C. When it is deemed to have attained the bath temperature it is withdrawn, drained of all superfluous zinc, and then immersed in a water bath. Salammoniac is used as a flux.

Objects such as rods, wires, strips, or plates may be drawn through the bath, and wiped mechanically with asbestos wipers as they leave the bath. It is often considered advantageous to add a zinc-aluminium alloy consisting of about 20 per cent. of aluminium to the molten zinc in order to give better fluidity. The frosted appearance of galvanized articles, such as steel sheets, is obtained by adding *tin* to the zinc.

The additional weight due to hot galvanizing is about 2 to 3 ounces per square foot.

When zinc is deposited electrolytically in a sulphate bath the coating obtained weighs about 1 ounce per square foot, so that this method is preferable in cases where weight economy is the first consideration.

Zinc-coated parts, whilst resisting ordinary atmospheric corrosive effects, are quickly corroded by sea water, tunnel and flue gases, and similar causes.

Electrolytic Zinc-Iron Method.

A method* has been developed for coating steel articles with pure electrolytic iron, and afterwards with zinc.

It is well known that the purer the iron is, the less liable it is to pitting and corrosion, and that chemically pure iron is the most rustless form of the metal.

The above-mentioned process, termed "ferro-zincing," takes advantage of these facts by coating the steel surface with almost pure iron, electrolytically, the only impurity being hydrogen; the presence of this latter element is considered an

* Sherard Cowper-Coles. See *Engineering*, June 12, 1914.

advantage, as it makes the iron slightly more electro-positive to the underlying steel. The process is a "cold" one, so that it does not affect the strength properties of the steel treated.

It has been found in practice to be advantageous to coat the electrolytic iron surface with zinc, as a zinc coating with an intermediate layer of pure iron-hydrogen alloy gives a greatly increased life to ordinary steel tube or plate.

Sherardizing.

This process* consists in first pickling the articles as for hot galvanizing and then packing them in pulverized zinc or zinc dust, to which zinc-oxide, with a small quantity of powdered charcoal, is added. The whole is heated in a closed air-tight retort to a temperature below the melting-point of zinc, usually from 250° to 320° C.

The period of the process varies from one to several hours, depending upon the size of the articles and of the retort; mechanical agitation, or rotation of the retort, is found to give a more even coating. The retort is allowed to cool down gradually after the above process.

In order to prevent caking, to reduce the amount of zinc oxide necessary, and to give a brighter finish, a quantity of sand is sometimes mixed with the zinc dust.

It has been shown that this method of alloying zinc with iron at a temperature below the melting-point of zinc is attended by a certain hardening effect.

The results of this process give a zinc surface similar to that obtained by the ordinary galvanizing process.

The Bower-Barff Process.

This process,† which is largely used for small hardware articles, consists in heating the steel or iron parts to about 980° C. in a closed chamber; superheated steam at a tem-

* Patented by S. Cowper-Coles in 1902.

† Trans. Amer. Inst. Mech. Engineers, A. S. Bower, 1882, p. 329; *Journ. Iron and Steel Inst.*, F. S. Barff, 1877, p. 356; Trans. Amer. Inst. Mech. Engineers, iv., p. 351.

perature of about 540° C. is then injected into the chamber. The steam is decomposed, and the oxygen liberated acts upon the iron, forming magnetic oxide of iron as a protective coating.

In place of the steam, air and carbon monoxide may be used. Another variation of the original method consists in subjecting the articles, which have been previously heated to about 870° C., to the superheated steam for a period of about half an hour, and then to produced gas for another 15 to 30 minutes; the object of the produced gas, which contains carbon monoxide, is to reduce any red oxide of iron formed.

This process may be repeated several times in order to increase the thickness of the coating, and it is found that cast iron and steel require more heat than ordinary iron.

In the "Wells process," which is an improvement upon the above, the superheated steam and producer gas are introduced at the same time.

The coating obtained by this process is a grey colour, and if not too thin will withstand rough treatment. It will withstand the action of salt water, acid fumes, and ordinary atmospheric influences, and the surface may be painted or enamelled. The grey colour may be changed to black by boiling. Articles are found to slightly increase in size by this process.

The Gesner Process.

This commercial process of Dr. Gesner* possesses the advantage that articles do not increase in size, nor are they distorted.

The process consists in heating the articles in a retort to a temperature of about 650° C. for about 20 minutes, and then allowing partially decomposed steam (which has been passed through a red-hot pipe) to act upon the articles for another 30 minutes. At the expiration of this period, a hydrocarbon such as naphtha is introduced, and is allowed to act upon the articles for about 15 minutes. When the temperature of the retort has fallen to about 430° C. the articles are withdrawn

* *Journ. Iron and Steel Inst.*, 1890, p 850.

The Bontempi System.

This process* is employed for rust-proofing sheet steel and iron, chains, bolts and nuts, and similar objects. It consists in heating the articles, which are disposed upon shelves in a metal cage in a muffle heated by means of Bunsen gas burners, to a certain temperature, after which superheated steam is turned on and allowed to act upon the parts for about half an hour. Finally, chemical fumes at a high temperature are allowed to replace the superheated steam, after which the cage is run out of the muffle on a trolley, and brought quickly under a metal cover or box, which is lowered over the cage to enable the articles to cool slowly.

It is stated that the thickness of the protective layer is about $\frac{2}{1000}$ of an inch.

Lead Coatings.

Lead coatings are sometimes applied to iron and steel articles for protective purposes, and provided that the lead is perfectly alloyed or bonded, it is very effective. The electrolytic method of depositing lead does not yield reliable results, the coating being porous, so that the lead-dipping process is preferred.

Terne sheets, which are frequently employed in place of tinned iron sheets, are made by dipping cleaned and pickled steel or iron sheets into molten lead.

Many articles are now coated by dipping with tin-lead alloys and wiping; the interiors of domestic iron and cast iron utensils, steel pipe, and other fittings are frequently coated with these alloys.

Aluminium Coatings.

Iron and steel work is sometimes protected by electrolytically coating with aluminium, or aluminium alloys. A high voltage is required for this process.

These coatings, when made from the correct alloys, possess

* For fuller particulars *vide* the *Autocar*, November 20, 1915.

the advantages of lightness, and possess a good appearance, but they are not always impervious to sea water influence.

Nickel Plating.*

Many automobile and aircraft fittings and parts are now nickel plated for protective and for appearance purposes. Nickel* itself is a silvery-white metal having a specific gravity of from 8·3 to 8·9; it is ductile, hard, and almost as strong as iron. It has a melting-point of about 1650° C.

It has been found that whilst nickel plating is very suitable for metal parts which are not subjected to reversed loadings, yet in the case of metal wires and thin plates, springs and similar objects, the nickel has a tendency to crack and to peel off.

In many cases nickel plating is attended with an appreciable hardening effect, and for this reason the process of nickel plating petrol and oil pipes has been abandoned by many automobile and aircraft manufacturers.

Rust-Proofing Cast Iron.

There are many methods for effectively protecting cast iron from corrosion.

Many of the bituminous paints and varnishes previously mentioned are suitable for this purpose, but the following notes refer to special methods which have been recently developed for the purpose of giving more permanent results.

(1) The Silicate Coating Method.

When iron is cast in the sand mould, it usually obtains a coating of silicates (derived from the sand itself), which forms an effective protecting surface.

A process, known as *Ward's Inoxidizing Method,*† coats the cast or wrought iron articles with silicates by immersion in a suitable bath of soluble silicates or by means of a brush, and afterwards, when dry, exposes the coated articles to a suffi-

* *Vide* "Nickel and its Alloys," Chapter IV., Vol. II., of this work.

† Spon's "Workshop Recipes," vol. iv., p. 38.

ciently high temperature to melt the silicates, which run and fill all of the pores. After cooling, a dead-black dense and uniform coating is obtained which does not crack or corrode. It is stated that excellent effects may be obtained by adding to the silicate pigments used for colouring glass.

(2) **Coal-Tar Method.**

A very effective lustrous black coating, impervious to acids or atmospheric action, can be given to cast iron and steel bodies by heating them upon a wire tray in a closed iron box, containing a layer of crushed blacksmith's coal at the bottom, to a red heat.

The coal dust gives off tarry constituents which cover the metal parts, and, if the heating is continued until the evolution of gas ceases, and the box is allowed to cool slowly, the best results are obtained.

(3) **Inoxidizing Process.**

A method frequently employed for protecting the surfaces of cast-iron articles, such as domestic ware, fireplaces, water-pipes, ornamental railings and fittings, consists in heating the parts, which are placed in shelves or on hooks in an iron truck, in a reverberatory furnace of special construction, at a temperature of from 600° to 700° C. for a period of about 15 minutes, the atmosphere being an oxidizing one.

The atmosphere is then changed to a reducing one (that is, to one containing no oxygen) for another period of about 20 minutes.

The colour of the articles, when cool, is a slate one, and they may be further protected by enamelling or painting.

Oxy-Oil Quenching Method.

A method which has been widely employed for rust-proofing cast-iron parts such as fuses, castings, machined parts, etc., consists in first removing all grease from the bodies by washing them in boiling caustic soda and in hot water, and next in heating them to about 700° to 750° C. in a special furnace,

in which an oxidizing atmosphere is maintained by means of an excess of air supply or similar methods.

The parts are then oil-quenched in two stages, firstly by means of a preliminary short immersion in oil, and then by a final immersion in oil to cool right out. The object of the preliminary immersion is to relieve part of the temperature stresses which would otherwise result from a single immersion. Special furnaces are now available in which the articles are hooked upon or placed in the segments of an endless chain conveyer, which carries them slowly through the oxidizing furnace, and first into one oil medium and then into the second.

For this purpose gas-fired furnaces are very suitable, as the air and gas supplies can be independently regulated so as to obtain the necessary temperature and oxidizing atmosphere. The coating obtained by this process is a black one.

It is essential to keep the air for admission dry and the oil bath cool. It is stated* that about 330 pounds of small cast-iron bodies can be coated per hour with a total gas consumption of 1·60 cubic feet per pound of metal treated.

The Corrosion of Copper.

Copper, when exposed to the air, oxidizes very slowly, and in time becomes coated with copper carbonate or verdigris, a light blue coloured salt.

Salt water and distilled water exert a much more rapid action, particularly when air is present; the action is one of chemical oxidation.

The surface of copper can be protected by giving it a coating of red oxide of copper; it is stated that the Japanese cast copper under water, the metal and the water both being heated beforehand, in order to obtain their characteristic rose-coloured tint, due to copper oxide. When copper is heated in steam to a high temperature cuprous oxide is formed upon its surface, which affords a fairly permanent protective coating.

It is usual to varnish or lacquer copper articles intended to retain their original polish, and there are many varnishes and lacquers available for the purpose.

* The Davis Furnace Company.

The Corrosion of Brass.

A considerable amount of research work has been done by the Corrosion Committee of the Institute of Metals, and several reports have been issued dealing with the subject.

The following is an extract from a description* in the Fourth Report, of the actions which take place when certain metals and alloys, such as brass, corrode in distilled and sea water.

It is stated that the action of these liquids upon metallic zinc and upon copper is one of chemical oxidation rather than an electro-chemical action.

"The action of distilled water on 70 : 30 brass is considered to be the chemical oxidation of the copper and zinc and the partial solution of the oxidized products. Much of the zinc, in the presence of carbon dioxide, passes into solution, and part of the copper. The residue of both metals remains on the surface of the alloy as an oxide scale, and this becomes further oxidized and altered at certain spots which become covered with thick deposits of the products of attack. Such deposits are porous, and allow, and probably accelerate, local attack on the underlying metal. The attack is accompanied by redeposition of copper by displacement by the zinc either electro-chemically or otherwise, and precipitation of cuprite. There are signs of slight local dezincification at such places, but the attack over the general surface of the alloy is complete corrosion. The positions at which local attack and pitting take place are not determined by the variation in the electrical properties of the original metal, but by the conditions of the experiment. In the presence of dilute acids, such as hydrochloric and sulphuric, local action of the type described does not occur, since there is little or no local accumulation of oxidation products. On the other hand, the absence of carbon dioxide retards the action. From the analytical data it appeared that the local action in the case of distilled water increased with time, while the rate of general corrosion over the whole specimen fell off. These facts suggest the fallacy of loss of weight test, since local action is more important practically than general corrosion.

"The action of sea water on brass has been studied on the same lines as that of distilled water. The action is considered to be similar in type. Local pitting and dezincification are due to the accumulation of the products of corrosion. Under certain conditions redeposition of copper may occur. The rate of general corrosion is much greater than that in distilled water, and does not fall off so rapidly with time. At the ordinary temperature there is less tendency to local dezincification.

"The ordinary 70 : 30 brass tube of commerce is not liable to any electrolytic action set up by anodic and cathodic areas inherent in its surface, even in the presence of good electrolytes such as sea water. It is corroded, under

* *Times* Engineering Supplement, April, 1919.

normal conditions, by a slow chemical action, which produces a slight roughening of the surface, but no well-defined pitting. Unless this action were speeded up locally by factors independent of the tube, the life of a tube would normally be 15 to 20 years or more in the case of deep sea water, and many types of neutral fresh water. If acid be present in the water in the proportions of only a few parts per 100,000, the speed of attack is greatly increased, the action being a general thinning of the tube. Neutralization is quite effective in stopping this increased action.

"The following conditions are set forth as those under which a tube would have a normal life of 20 years. In practice tubes fail sooner because the normal slow roughening of the tube by chemical oxidation is locally speeded up by factors which are, for the most part independent of the tube (*a*) Only clear water to enter the tube, or water that will not deposit suspended matter. (*b*) The water must be free from gases in suspension, and must not contain more than the normal amount of air in solution. (*c*) The water must be neutral or not more than very slightly alkaline. It must be free from ammonia, and certain other specially harmful substances which are, however, of comparatively rare occurrence in technical waters. (*d*) The temperature of the cooling water in the hottest part of the condenser should not exceed 35° C. (*e*) The speed of the water should be about 5 or 6 feet per second. (*f*) The steam should be properly distributed in the condenser, according to the best modern practice.

"As it does not seem likely that the problem of preventing local pitting will be solved by improvements in composition, it may in certain circumstances be desirable to add to the resisting power of the tube by special treatment before it goes into use. Such treatment, for instance, may be the production on the tube of a resistant scale by artificial means. Such a scale may consist of oxide, calcium carbonate, or a basic salt, or a mixture of these substances. The simplest, but not the most efficient, case of such a scale is an oxide scale produced upon the alloy by treatment in an annealing furnace in an oxidizing atmosphere, and a number of experiments have been made with tubes treated in this way.

"The treatment in the case of 70 . 30 brass, lead-brass, or Admiralty alloy is to heat the finished tube in an oxidizing atmosphere for half an hour at a temperature of about 260° to 300° C. It is then put into use with the oxide scale on it—*i.e.*, without pickling or further treatment. It has been found that this heat treatment does not affect the mechanical properties of the tube sufficiently to interfere with the making of a tight joint by the use of ferrules. (The heating periods and temperatures are different for metals or alloys other than those mentioned.) The process is known as the pre-oxidizing process. It is important that the tubes treated by this process should have a good surface, smooth and uniform. Harm may result if the heating temperature much exceeds the limits stated.

"Tubes of various types of brass, treated in the way indicated, have given good results so far at Brighton, in comparison with ordinary tubes of similar composition, but it is not yet certain that such tubes will resist the active attack set up by certain deposits. A considerable number of treated tubes are under test in various parts of the country, under different sets of conditions, and the results of these tests will be reported in due course

Preliminary tests seem to show that treated lead-brass and Admiralty tubes resist dezincification to a marked degree in ordinary sea water.

"Finally, it must be emphasized that it is not likely that either tubes treated as described, or any other type of tube producible commercially, will be found satisfactory under all conditions. A tube and its treatment must be chosen to meet the particular conditions in which it will be used, but it is hoped that the number of types of tube and treatments required will be small. They may, perhaps, be eventually reduced to two, a copper type alloy and a selected brass alloy."

Protection of Aircraft Parts.

It has been stated that the average life of an aeroplane is relatively so short that very efficient protective measures are not of primary importance; this is, however, not in accordance with the facts. The author is acquainted with several cases of machines having been in intermittent use for over two years; the average machine in peace time should last at least a year.

Machines are subjected not only to atmospheric influences in unheated hangars, but also to great changes in temperature and humidity whilst flying, so that it is necessary to protect all exposed parts from atmospheric effects.

The matter of efficient protection is important also from the point of view of strength, for the effect of rusting or corrosion upon the cross-sectional area of thin steel tubes, wires, and thin sheet metal parts may be appreciable.

It is also possible that the exhaust gases of the engine, which are highly corrosive, may come into contact with exposed metal parts.

The methods adopted for protecting metal fittings, when these are not made from "stainless steel" or non-corrodible alloys, is usually to Borrodize (or finely galvanize), Sherardize, or Coslettize the parts. In many cases dull coppering and nickel plating has been employed with success. The tubular frameworks of control surfaces, body and wing structures, should be varnished internally with a suitable "shell" or "tube" varnish.

All internal wires, tubes, and fittings are now painted with efficient metal "primers" or "paints," and in many cases

tubular frame works are bound with Egyptian tape before covering with fabric.

Ordinary galvanizing is not employed to any extent, owing to the appreciable weight increase, but many bracing cables consist of finely galvanized wires.

Most of the streamlined, round bracing wires are at the present time merely kept coated with vaseline or grease; this is an unsatisfactory measure, and should be replaced by a more permanent means of protection. No doubt the employment of "stainless" steels for bracing wires, clips, etc., will simplify the protective methods adopted.

Steel cables, whether galvanized* or not, are now invariably coated with a graphite or non-corrodible paint or grease. Aluminium alloy parts, such as the frameworks of rigid airships, aeroplane parts, etc., are now always varnished all over for protection purposes. Gun parts and instrument fittings are usually given a "blued" or "browned" surface, these oxide films having been found to give a certain measure of protection.

Aluminium alloys are considerably more durable in the open air than ordinary steel, but most of the alloys at present in use do not stand up to sea-water action. For this reason the use of aluminium-alloyed fittings for under-water and exposed parts has been largely abandoned in favour of malleable bronzes such as the Delta metals, etc. Aluminium wing and fuselage frameworks are now invariably varnished with a chemically neutral varnish, and when so treated give very satisfactory results.

* Nickel-plating of flexible cables is not satisfactory, owing to the flexible nature of the cable, causing cracking, etc.

APPENDICES

APPENDIX I

FERROUS AND OTHER ALLOYS

FERRO-CHROME.

FERRO-MANGANESE

SILICO-CALCIUM-ALUMINIUM.

SILICO-MANGANESE.

FERRO-SILICON.

SILICO-MANGANESE-ALUMINIUM.

FERRO-SILICON-ALUMINIUM.

FERRO-TUNGSTEN.

OTHER FERRO ALLOYS.

SPIEGELEISEN.

APPENDIX I

FERROUS AND OTHER ALLOYS

Ferro-Chrome.

THESE alloys are generally made in the electric furnace, and the composition can be varied between fairly wide limits. Ferro-chrome contains from 1 to 10 per cent. of carbon, according to the grade, and from 54 to 64 per cent. of chromium. It is widely used in the manufacture of aircraft and automobile steels, and for gun-steels, projectiles, etc.; when added to the ordinary molten steel in the requisite amounts, it imparts to the correct amount of chromium to the finished product.

It is usually employed in conjunction with nickel, tungsten, molybdenum, or vanadium in alloy steels.

The carbon content of ferro-chrome for general foundry and steel-making purposes is from 8 to 9 per cent.

It is usual to include in the composition from 2 to 5 per cent. of silicon, in order to protect the chromium from oxidation. The grades of ferro-chrome are usually based upon the carbon contents, as follows:

TABLE I.—COMPOSITIONS OF DIFFERENT FERRO-CHROMES.*

Element.	*Grade A.* 8 *to* 10 *per Cent.*	*Grade B.* 7 *to* 8 *per Cent.*	*Grade C.* 5 *to* 6 *per Cent.*	*Grade D.* 3 *to* 4 *per Cent.*	*Grade E.* *Mean of* 1 *per Cent.*
Chromium ..	54·50	63·50	64·00	64·00	63·50
Iron	22·00	21·50	28·50	31·00	35·00
Carbon ..	9·50	7·50	5·50	3·50	0·60
Silicon ..	2·25	5·30	0·40	0·40	0·20
Aluminium ..	0·80	0·80	0·50	0·40	0·10
Manganese ..	0·15	0·15	0·15	0·15	0·10
Calcium ..	0·25	0·25	0·25	0·30	0·35
Sulphur ..	0·04	0·04	0·04	0·04	0·03
Phosphorus ..	0·03	0·03	0·03	0·02	0·02

* Paul Girod.

Ferro-Manganese.

This is an alloy of manganese and iron which is used for purifying and deoxidizing iron and steel and for foundry purposes. The following are the ranges of compositions:

Manganese	41 to 88 per cent.
Silicon	0·10 to 0·65 ,,
Phosphorus	0·09 to 0·20 ,,
Carbon	5·62 to 7·00 ,,
Sulphur	nil.

Silico-Calcium-Aluminium.

This is one of the fluxing compounds employed in steel making; it not only oxidizes the impurities, such as sulphur, but also gives greater fluidity to the molten metal.

The following is a typical composition:

Silicon	50 to 55 per cent.
Calcium	18 to 22 ,,
Iron	12 to 15 ,,
Aluminium	4 to 5 ,,
Carbon	1 to 1·25 ,,
Magnesium	about 0·35 ,,
Manganese	,, 0·22 ,,
Sulphur	,, 0·075 ,,
Phosphorus	,, 0·03 ,,

Silico-Manganese.

This product is obtained in the electric furnace from the silicate minerals and manganese.

The following are the two grades usually made:

	Grade A.	*Grade B.*
Silicon	60 to 70	50 to 60
Manganese	20 to 25	22 to 25
Iron	remainder.*	remainder.*

Most of the ferrous alloys used in metallurgical practice are now made in the electric furnace,† but some, such as ferro-manganese and spiegeleisen, are found naturally. The following are a few of the more commonly employed alloys:

* Other elements such as aluminium, calcium, magnesium, carbon, sulphur, and phosphorus are present in small amounts.

† For fuller information *vide* "Les Alliages Ferro-Métalliques de la S.A.E. Procédés Paul Girod" (Ugine).

Ferro-Silicon.

In the natural state this alloy contains from 10 to 12 per cent. of silicon; the amount rarely exceeds 15 per cent.

The higher content alloys are made in the electric furnace, using siliceous materials and iron having practically no sulphur or phosphorus. The different grades of ferro-silicon, contain (*a*) 25 to 30 per cent., (*b*) 45 to 50 per cent., (*c*) 75 to 80 per cent., and (*d*) 90 to 95 per cent., of silicon.

Silico-Manganese-Aluminium.

This alloy is made in two grades having the undermentioned compositions:

	Grade A.	*Grade B.*
Silicon	18 to 20 per cent.	9 to 11 per cent.
Manganese	18 to 22 ,,	9 to 11 ,,
Aluminium	9 to 12 ,,	4½ to 6 ,,
Iron	remainder.	remainder.

This alloy is used for making the metal for guns and projectiles and high grade steels, owing to its deoxidizing properties.

Ferro-Silicon-Aluminium.

This alloy resembles the previous one in its deoxidizing properties and it is produced electrically.

The composition is as follows:

Silicon	45 per cent.
Aluminium	12 to 15 per cent.
Iron	remainder.

Ferro-Tungsten.

This alloy is used in connexion with the manufacture of tungsten magnet and high-speed tool steels, to impart the correct amount of the element to the finished metal. It is obtained in the electric furnace from the tungsten ores wolframite or wolframate of iron and manganese.

The highest tungsten content of high-speed steels is from 20 to 25 per cent., which is usually associated with about 6 per cent. of chromium.

Ferro-tungsten contains from 70 to 80 per cent. of aci "tungstique."

Other Ferro Alloys.

Alloys of iron, with molybdenum, vanadium, titanium, and other rare elements employed in special steels and alloys, are now manufactured, usually in the electric furnace, for metallurgical purposes. The following are typical compositions of some of these products:

TABLE II.

	Ferro-Titanium.	*Ferro-Vanadium.*	*Ferro-Molybdenum.*	*Ferro-Phosphorus.*
Iron	42·16	64·22 to 40·00	18·50	Balance.
Carbon ..	3·28	1·42 to 4·00	4·00	0·27 to 0·30
Silicon ..	1·21	0·12 to 0·30	0·20	0·50 to 0·84
Aluminium ..	0·30	0·12 to 0·10	0·10	—
Calcium ..	—	—	0·15	—
Manganese ..	—	0·12 to 0·30	0·15	3·00 to 5·90
Sulphur ..	0·03	0·03	0·03	0·16 to 0·33
Phosphorus ..	0·20	0·009 to 0·04	0·03	15·70 to 20·50
Molybdenum ..	—	—	75·00	—
Titanium ..	53·0	—	—	—
Vanadium ..	—	34·10 to 55·00	—	—

Other ferro alloys include ferro-uranium, ferro-boron, and ferro-tantulum.

Spiegeleisen.

Spiegeleisen is an iron-manganese carbide, which occurs in ore deposits; it crystallizes in the rhombic system. This ferrous product contains from 10 to 30 per cent. of manganese and from 4 to 5 per cent. of carbon, with small quantities of silicon, sulphur, and phosphorus.

It is widely used in iron smelting and for foundry purposes to impart the proper amount of manganese to steels and bronzes, etc., and to purify and render more fluid the metals.

The following are the approximate ranges of compositions:

Manganese	9·25 to 29·75 per cent.
Silicon	0·42 to 0·95 ,,
Phosphorus	0·06 to 0·09 ,,
Sulphur	traces.
Carbon	3·94 to 5·20 ,,

APPENDIX II

PHYSICAL AND MECHANICAL PROPERTIES OF METALS AND ALLOYS

TABLE I.—PHYSICAL CONSTANTS OF METALS.

Metal.	*Symbol.*	*Atomic Weight. O=16*	*Atomic Volume.*	*Specific Gravity.*	*Specific Heat.*	*Melting Point- ° C.*	*Coefficient of Linear Expansion.*	*Therm. Cond. C.G.S. Units.*	*Elect. Cond. C.G.S. Units.*
Aluminium	Al	27·1	10·6	2·56	0·218	657	0·0000231	0·502	390,000
Antimony	Sb	120·2	17·9	6·71	0·051	632	0·0000105	0·042	31,471
Arsenic	As	74·96	13·2	5·67	0·081	450 under pressure	0·0000055	—	32,425
Barium	Ba	137·37	36·3	3·78	0·047	850	—	—	—
Bismuth	Bi	208·0	21·2	9·80	0·031	266	0·0000162	0·019	9,091
Cadmium	Cd	112·4	13·2	8·60	0·056	322	0·0000306	0·219	99,800
Cæsium	Cs	132·81	71·0	1·87	0·048	26	0·0001316	—	25,400
Calcium	Ca	40·09	25·5	1·57	0·170	780	—	—	150,818
Cerium	Ce	140·25	21·0	6·68	0·045	623	—	—	—
Chromium	Cr	52·0	7·6	6·80	0·120	1482	—	—	—
Cobalt	Co	58·97	6·9	8·50	0·103	1464	0·0000123	—	106,140
Columbium	Cb	93·5	13·0	7·2	0·071	1950	—	—	—
Copper	Cu	63·57	7·1	8·93	0·098	1084	0·000167	0·924	640,615
Gallium	Ga	69·9	11·8	5·90	0·079	30	—	—	—
Glucinum	Gl	9·1	4·7	1·93	0·621	Below 960	—	—	—
Gold	Au	197·2	10·2	19·32	0·031	1064	0·0000144	0·700	455,166
Indium	In	114·8	15·5	7·42	0·057	155	0·0000417	—	112,400
Iridium	Ir	193·1	8·6	22·42	0·033	1950	0·0000070	—	—
Iron	Fe	55·85	7·2	7·86	0·110	1505	0·0000121	0·147	110,314
Lanthanum	La	139·0	22·7	6·10	0·045	810	—	—	—
Lead	Pb	207·1	18·2	11·37	0·031	327	0·0000292	0·084	49,067
Lithium	Li	7·0	13·0	0·54	0·941	186	—	—	119,428

Magnesium	Mg	24·32	13·9	1·74	0·250	633	0·0000269	0·343	229,616
Manganese	Mn	54·93	7·3	7·50	0·120	1207	—	—	—
Mercury	Hg	200·0	14·7	13·59	0·032	−39	0·0000610	0·015	10,630
Molybdenum	Mo	96·0	11·2	8·60	0·072	2500	—	—	—
Nickel	Ni	58·68	6·7	8·80	0·108	1427	0·0000127	0·141	144,196
Osmium	Os	190·9	8·5	22·48	0·031	2500	0·0000065	—	105,300
Palladium	Pd	106·7	9·3	11·50	0·059	1535	0·0000117	0·168	97,857
Platinum	Pt	195·0	9·1	21·50	0·032	1745	0·0000089	0·166	91,600
Potassium	K	39·1	45·5	0·86	0·170	62	0·0000841	—	141,990
Rhodium	Rh	102·9	8·5	12·10	0·058	1660	0·0000085	—	—
Rubidium	Rb	85·45	55·8	1·53	0·077	38	—	—	—
Ruthenium	Ru	101·7	8·3	12·26	0·061	1800	0·0000096	—	—
Scandium	Sc	44·1	17·6	2·5	0·153	1200	—	—	—
Silver..	Ag	107·88	10·2	10·53	0·056	962	0·0000192	0·993	681,198
Sodium	Na	23·0	23·8	0·97	0·290	95	0·0000710	0·365	253,973
Strontium	Sr	87·62	34·5	2·54	—	800	—	—	45,708
Tantalum	Ta	181·0	14·1	12·8	0·033	2910	0·0000079	—	60,600
Tellurium	Te	127·5	20·4	6·25	0·049	440	0·0000167	—	46,600
Thallium	Tl	204·0	17·2	11·85	0·033	303	0·0000302	—	56,712
Thorium	Th	232·42	20·9	11·10	0·028	1450	—	—	—
Tin	Sn	119·0	16·3	7·29	0·055	232	0·0000232	0·155	76,640
Titanium	Ti	48·1	13·5	3·54	0·13	2000 ?	—	—	—
Tungsten	W	184·0	9·6	19·10	0·034	3100	—	—	11,600
Uranium	U	238·5	12·8	18·7	0·028	—	—	—	—
Vanadium	V	51·2	9·3	5·50	0·125	1680	—	—	—
Yttrium	Yt	89·0	23·4	3·80	—	1000 ?	—	—	—
Zinc	Zn	65·37	9·1	7·15	0·094	419	0·0000291	0·269	171,381
Zirconium	Zr	90·6	21·8	4·15	0·066	1500	—	—	—

TABLE II.—THERMAL CONDUCTIVITIES OF METALS AND ALLOYS (IN ORDER OF CONDUCTIVITY.)

No.	*Metal or Alloy.*	*Thermal Conductivity.**	*Temperature.*
1	Silver (pure)	1·006	18° C.
2	Copper (pure)	0·918	18° C.
3	Gold	0·700	18° C.
4	Aluminium	0·504	18° C.
5	Mangesium	0·376	0° to 100° C.
6	Tungsten	0·35	18° C.
7	Zinc (pure)	0·265	18° C.
8	Brass†	0·260	17° C.
9	Cadmium (pure)	0·222	18° C.
10	Palladium	0·168	18° C.
11	Platinum	0·166	18° C.
12	Iron (pure)	0·161	18° C.
13	Tin (pure)	0·155	18° C.
14	Iron, wrought	0·144	18° C.
15	Nickel (97 per cent.)	0·142	18° C.
16	Iron, cast	0·114	54° C.
17	Steel (1 per cent. C)	0·108	18° C.
18	German silver	0·070	0° C.
19	Platinoid	0·060	18° C.
20	Constantan	0·054	18° C.
21	Manganin	0·053	18° C.
22	Antimony	0·044	0° C.
23	Mercury	0·0197	17° C.
24	Bismuth	0·0194	18° C.

* The thermal conductivity is the number of (gramme) calories conducted per square centimetre per second across a slab of the substance 1 cm. thick, having a temperature gradient of 1° C. per cm.

† 70 copper, 30 zinc.

TABLE III.—SPECIFIC RESISTANCES OF METALS AND ALLOYS (IN ORDER OF CONDUCTIVITIES).

Metal.	*Specific Resistance.*
Silver	$1\cdot5$ to $1\cdot65 \times 10^{-6}$
Copper	$1\cdot6$ to $1\cdot8 \times 10^{-6}$
Gold	$2\cdot2$ to $2\cdot4 \times 10^{-6}$
Aluminium	$2\cdot9$ to $3\cdot2 \times 10^{-6}$
Magnesium	$4\cdot3$ to $4\cdot4 \times 10^{-6}$
Tungsten	$5\cdot0 \times 10^{-6}$
Iridium	$5\cdot3 \times 10^{-6}$
Zinc	$6\cdot1 \times 10^{-6}$
Brass	6 to 9×10^{-6}
Phosphor bronze	5 to 10×10^{-6}
Iron	9 to 11×10^{-6}
Palladium	$10\cdot7 \times 10^{-6}$
Platinum	11 to $11\cdot2 \times 10^{-6}$
Nickel	$11\cdot8$ to $12\cdot0 \times 10^{-6}$
Tantulum	$14\cdot6 \times 10^{-6}$
Lead	$19\cdot8$ to $20\cdot8 \times 10^{-6}$
German silver	16 to 40×10^{-6}
Platinoid	$34\cdot5 \times 10^{-6}$
Antimony	$40\cdot5 \times 10^{-6}$
Manganin	42 to 44×10^{-6}
Constantan	$49\cdot0 \times 10^{-6}$
Bismuth	$119\cdot0 \times 10^{-6}$

Note.—The specific resistance is the resistance in ohms of a rod 1 cm. long and 1 square cm. cross-section of 0° C.

TABLE IV.—DUCTILITY AND MALLEABILITY OF COMMON METALS.

No.	*Order of Ductility of Common Metals.**	*Order of Malleability of Common Metals.†*
1	Gold	Gold
2	Silver	Silver
3	Platinum	Copper
4	Iron	Tin
5	Nickel	Platinum
6	Copper	Lead
7	Zinc	Zinc
8	Tin	Iron
9	Lead	Nickel

* Ductility is the property which enables metals to be drawn out into wire.

† Malleability is the property of permanently extending, under pressure, in all directions, without rupture.

TABLE V.—ORDER OF HARDNESSES OF METALS.* (Brinell.)

No.	*Metal.*	*Hardness.*	*No.*	*Metal.*	*Hardness.*
1	Air-hardened nickel-chrome steel	700	8	Brass	63
			9	Silver	59
2	High carbon steel (1·25 C)	300	10	Antimony	55
			11	Zinc	46
3	Medium carbon steel (0·45 C)	200	12	Gold	45
			13	Aluminium	38
4	Phosphor bronze ..	130	14	Phosphor tin	19·7
5	Bell metal	124	15	Tin	14·5
6	Mild steel (0·1 C) ..	100	16	Rose-metal	6·9
7	Rolled copper	74	17	Lead	5·7

* Also see p. 151 *et seq.*

TABLE VI.—PROPERTIES OF STEELS.

Material.	*Tensile Breaking Stress.*	*Elastic Limit.*	*Extension.*	*Shearing Strength.*	*Remarks.*
	Tons per Square Inch.	Tons per Square Inch.	Per Cent	Tons per Square Inch	
Mild steel plate	24 to 28	16 to 20	20 to 30	17·9	—
Bright drawn mild steel	30 ,, 40	28 ,, 35	15 ,, 35	19·0	Elongation on 2".
Siemens' forged mild steel	29 ,, 35	17 ,, 19	20 ,, 25	—	—
Fluid compressed steel	50 ,, 55	40 ,, 45	—	—	—
Rivet steel	22 ,, 26	15 ,, 20	26	12·5	—
Tool steel (annealed)	45 ,, 55	35 ,, 40	20	—	—
,, ,, (hardened)	60 ,, 70	45 ,, 60	8 to 12	—	—
Axle steel	35 ,, 40	18 ,, 25	20 ,, 25	—	—
Tyre steel	50 ,, 55	40 ,, 45	10 ,, 15	—	—
Spring steels (treated)	55 ,, 75	30 ,, 35	5 ,, 14	—	—
Steel castings	26 ,, 35	12 ,, 17	15 ,, 20	—	—
Case-hardening steel (annealed)	34	28	44	—	Elongation on 2".
,, ,, (case-hardened)	46	35	3·2	—	Ubas steels.
Nickel Chrome Steels :					
(1) As rolled	50 to 85	40 to 75	16 to 22	—	—
(2) Air-hardened	90 ,, 115	80 ,, 100	8 ,, 12	—	Elongation on 2".
(3) Oil-hardened	100 ,, 125	85 ,, 100	8 ,, 12	—	
Chrome Vanadium Steels :					
(1) As rolled	50 ,, 60	40 ,, 50	25	—	Elongation on 2".
(2) Heat treated	110 ,, 120	100 ,, 105	6 to 8	—	,,
(3) For springs (treated)	110	64	4	—	—
Nickel Steel :					
(1) As rolled, 5 per cent. Ni	40 to 48	30 to 35	25	—	Elongation on 2".
(2) Oil-tempered, 5 per cent. Ni	85 ,, 95	80 ,, 88	12	—	,,
(1) As rolled, 3 per cent. Ni	40 ,, 44	28 ,, 34	25 to 30	—	,,
(2) Oil-tempered, 3 per cent. Ni	75 ,, 85	68 ,, 78	12 ,, 16	—	,,
(1) Case-hardening (annealed)	30 ,, 35	22 ,, 27	30	—	,,
(2) ,, (hardened)	65 ,, 75	58 ,, 65	14 to 18	—	,,

TABLE VII.—ELASTIC COEFFICIENTS.

In Pounds per Square Inch.

Material.	*Modulus of Elasticity (E).*	*Modulus of Rigidity (C).*
Cast iron: white	23,000,000	7,600,000
,, ,, grey	15,000,000	5,000,000
Wrought-iron bar	29,000,000	10,000,000
Mild steel plate	30,000,000	13,500,000
Rivet steel	30,000,000	13,000,000
Cast steel (untempered) ..	30,000,000	12,000,000
Copper plate	15,000,000	5,600,000
,, wire	17,000,000	5,000,000
Phosphor bronze	14,000,000	5,250,000
Aluminium: cast	12,500,000	3,400,000
,, sheet	13,500,000	4,800,000

Note.—The Modulus C is about $\frac{2}{5}$ E for most metals.

TABLE VIII.—WORKING STRESSES IN METALS IN POUNDS PER SQUARE INCH.

(*a*) FOR STEADY LOADS.

Material.	*Tension.*	*Compression.*	*Shear.*	*Torsion.*
Cast iron	4,200	12,000	2,200	5,000
Wrought iron	15,000	15,000	12,000	7,500
Mild steel plate	13,000 to 17,000	13,000 to 17,000	10,000 to 13,000	8,000 to 12,000
Nickel steel plate..	16,000 ,, 18,000	16,000 ,, 18,000	13,000 ,, 14,000	10,000 ,, 15,000
Cast steel	17,000 ,, 21,000	17,000 ,, 21,000	13,000 ,, 17,000	12,000 ,, 16,000
Nickel chrome steel (unhardened) ..	17,000 ,, 23,000	17,000 ,, 23,000	13,500 ,, 18,000	11,000 ,, 16,000
,, ,, ,, (hardened).. ..	35,000 ,, 46,000	35,000 ,, 46,000	26,000 ,, 36,000	20,000 ,, 30,000
Chrome vanadium (unhardened) ..	17,000 ,, 21,000	17,000 ,, 21,000	13,000 ,, 17,000	11,000 ,, 15,000
,, ,, (hardened)	36,000 ,, 50,000	36,000 ,, 50,000	27,000 ,, 40,000	21,000 ,, 35,000
Gunmetal	4,200	4,000	2,500	2,000
Phosphor bronze	10,000	7,000	5,000	4.000
Aluminium, sheet	6 000	4,000	1,800	1,000

(*b*) For loads varying from zero to a maximum, frequently as in the case of shocks, etc., multiply the above numbers by 0·66.

(*c*) For loads varying from a stress of one sign, through zero to a stress of the opposite sign, frequently, as in the case of a piston-rod, multiply the above numbers by 0·33.

TABLE IX.—PROPERTIES OF STEEL AND DURALUMIN TUBES.

Outside Diameter		3/8"	1/2"	5/8"	3/4"	7/8"	1"	1 1/8"	1 1/4"	1 3/8"	1 1/2"	1 5/8"
Decimal of Inch		0·37500	0·5000	0·6250	0·7500	0·8750	1·0000	1·1250	1·250	1·3750	1·5000	1·6250
24 S.W.G. 0·022	W	0·08400	0·1133	0·1426	0·1719	0·2002	0·2295	0·2588	0·2881	0·3172	0·3465	0·3768
	A	0·02440	0·0339	0·0417	0·0503	0·0590	0·0676	0·0762	0·0849	0·0935	0·1024	0·1108
	I	0·00038	0·0010	0·0019	0·0033	0·0054	0·0081	0·0116	0·0161	0·0215	0·0279	0·0356
	Z	0·00200	0·0039	0·0061	0·0089	0·0123	0·0162	0·0207	0·0257	0·0313	0·0373	0·0438
22 S.W.G. 0·028	W	0·10370	0·1441	0·1785	0·2157	0·2533	0·2907	0·3281	0·3655	0·4029	0·4403	0·4777
	A	0·03050	0·0415	0·0525	0·0635	0·0745	0·0855	0·0965	0·1075	0·1185	0·1295	0·1405
	I	0·00046	0·0011	0·0023	0·0042	0·0067	0·0101	0·0145	0·0201	0·0269	0·0351	0·0448
	Z	0·00250	0·0045	0·0075	0·0112	0·0153	0·0202	0·0258	0·0321	0·0391	0·0408	0·0552
20 S.W.G. 0·036	W	0·13010	0·1782	0·2264	0·2744	0·3223	0·3706	0·4185	0·4555	0·5[illegible]48	0·5627	0·6110
	A	0·03830	0·0524	0·0666	0·0807	0·0948	0·1090	0·1231	0·1372	0·1514	0·1655	0·1797
	I	0·00056	0·0014	0·0029	0·0050	0·0083	0·0127	0·0183	0·0254	0·0340	0·0442	0·0567
	Z	0·00300	0·0058	0·0093	0·0135	0·0190	0·0254	0·0326	0·0407	0·0495	0·0592	0·0698
18 S.W.G. 0·048	W	0·16760	0·2319	0·2968	0·3601	0·4240	0·4882	0·5522	0·6164	0·6803	0·7446	0·8085
	A	0·04930	0·0682	0·0870	0·1059	0·1247	0·1436	0·1624	0·1813	0·2001	0·2190	0·2378
	I	0·00067	0·0018	0·0037	0·0065	0·0107	0·0163	0·0236	0·0328	0·0440	0·0577	0·0740
	Z	0·00360	0·0072	0·0117	0·0175	0·0245	0·0326	0·0419	0·0524	0·0641	0·0770	0·0911
16 S.W.G. 0·064	W	0·21250	0·2980	0·3834	0·4689	0·5544	0·6399	0·7253	0·8108	0·8962	0·9817	1·0672
	A	0·06250	0·0876	0·1128	0·1379	0·1630	0·1882	0·2133	0·2385	0·2636	0·2887	0·3139
	I	0·00082	0·0021	0·0045	0·0082	0·0135	0·0207	0·0301	0·0421	0·0567	0·0746	0·0958
	Z	0·00420	0·0085	0·0144	0·0218	0·0308	0·0414	0·0536	0·0673	0·0826	0·0995	0·1179
14 S.W.G. 0·080	W	—	—	0·4658	0·5726	0·6794	0·7862	0·8930	0·9998	1·1066	1·2134	1·3202
	A	—	—	0·1370	0·1684	0·1998	0·2312	0·2626	0·2941	0·3255	0·3569	0·3883
	I	—	—	0·0052	0·0096	0·0160	0·0246	0·0361	0·0506	0·0685	0·0903	0·1162
	Z	—	—	0·0166	0·0256	0·0365	0·0493	0·0641	0·0809	0·0997	0·1204	0·1430
12 S.W.G. 0·104	W	—	—	—	—	0·8565	0·9953	1·1341	1·2730	1·4118	1·5506	1·6895
	A	—	—	—	—	0·2519	0·2927	0·3336	0·3744	0·4152	0·4561	0·4969
	I	—	—	—	—	0·0191	0·0298	0·0440	0·0620	0·0844	0·1117	0·1445
	Z	—	—	—	—	0·0436	0·0597	0·0783	0·0994	0·1228	0·1490	0·1778
10 S.W.G. 0·128	W	—	—	—	—	—	—	1·3631	1·5439	1·7048	1·8757	2·0466
	A	—	—	—	—	—	—	0·4009	0·4512	0·5014	0·5517	0·6019
	I	—	—	—	—	—	—	0·0506	0·0718	0·0984	0·1308	0·1697
	Z	—	—	—	—	—	—	0·0900	0·1149	0·1431	0·1743	0·2089

W = Weight in pounds per foot run. A = Cross-section area $\pi t\,(D - t)$. I = Moment of inertia $= \frac{\pi}{64}(D^4 - d^4)$.

Z = Modulus of resistance $= {}^{2I}/_{D} = \frac{A}{8}\left(\frac{D^2+d^2}{D}\right)$. D = Outside diameter. d = Inside diameter = D − 2t. t = Thickness.

Weights given are for steel tubes at 0·283 lbs. per cu. in. For duralumin multiply given weight by 0·361.
For aluminium multiply given weight by 0·328.

PROPERTIES OF STEEL AND DURALUMIN TUBES—*Continued.*

Outside Diameter		1¾"	1⅞"	2"	2⅛"	2¼"	2⅜"	2½"	2⅝"	2¾"	2⅞"	3"
Decimal of Inch		1·7500	1·8750	2·0000	2·1250	2·2500	2·3750	2·5000	2·6250	2·7500	2·8750	3·0000
24	W	0·4160	0·4353	0·4646	0·4939	0·5232	—	—	—	—	—	—
S.W.G.	A	0·1194	0·1281	0·1367	0·1455	0·1540	—	—	—	—	—	—
	I	0·0445	0·0548	0·0667	0·0802	0·0955	—	—	—	—	—	—
0·022	Z	0·0509	0·0585	0·0667	0·0755	0·0849	—	—	—	—	—	—
22	W	0·5157	0·5525	0·5899	0·6273	0·6647	0·7021	0·7395	—	—	—	—
S.W.G.	A	0·1515	0·1625	0·1735	0·1845	0·1955	0·2065	0·2175	—	—	—	—
	I	0·0562	0·0693	0·0844	0·1015	0·1207	0·1423	0·1661	—	—	—	—
0·028	Z	0·0642	0·0740	0·0844	0·0955	0·1073	0·1198	0·1329	—	—	—	—
20	W	0·6589	0·7069	0·7551	0·8031	0·8510	0·8993	0·9476	0·9955	1·0438	—	—
S.W.G.	A	0·1938	0·2079	0·2221	0·2362	0·2503	0·2645	0·2787	0·2928	0·3070	—	—
	I	0·0711	0·0879	0·1071	0·1289	0·1533	0·1807	0·2115	0·2456	0·2827	—	—
0·036	Z	0·0813	0·0938	0·1071	0·1213	0·1363	0·1522	0·1692	0·1871	0·2056	—	—
18	W	0·8728	0·9367	1·0001	1·0649	1·1291	1·1931	1·2573	1·3212	1·3855	1·4494	1·5137
S.W.G.	A	0·2567	0·2755	0·2944	0·3132	0·3321	0·3509	0·3698	0·3886	0·4075	0·4263	0·4452
	I	0·0931	0·1150	0·1404	0·1690	0·2014	0·2376	0·2780	0·3227	0·3721	0·4261	0·4851
0·048	Z	0·1064	0·1228	0·1404	0·1591	0·1790	0·2001	0·2224	0·2459	0·2706	0·2964	0·3234
16	W	1·1526	1·2381	1·3236	1·4090	1·4945	1·5800	1·6654	1·7509	1·8364	1·9218	2·0073
S.W.G.	A	0·3390	0·3641	0·3893	0·4144	0·4396	0·4647	0·4898	0·5150	0·5401	0·5653	0·5904
	I	0·1208	0·1495	0·1826	0·2203	0·2628	0·3104	0·3635	0·4224	0·4873	0·5586	0·6364
0·064	Z	0·1379	0·1595	0·1826	0·2073	0·2336	0·2614	0·2908	0·3218	0·3544	0·3886	0·4243
14	W	1·4270	1·5337	1·6405	1·7473	1·8541	1·9609	2·0677	2·1745	2·2813	2·3881	2·4949
S.W.G.	A	0·4197	0·4511	0·4825	0·5139	0·5454	0·5768	0·6082	0·6396	0·6710	0·7024	0·7338
	I	0·1466	0·1821	0·2227	0·2691	0·3215	0·3802	0·4456	0·5180	0·5983	0·6863	0·7825
0·080	Z	0·1676	0·1942	0·2227	0·2533	0·2858	0·3202	0·3565	0·3948	0·4351	0·4774	0·5217
12	W	1·8283	1·9672	2·1060	2·2448	2·3837	2·5225	2·6613	2·8002	2·9390	3·0779	3·2167
S.W.G.	A	0·5377	0·5786	0·6194	0·6603	0·7011	0·7419	0·7828	0·8236	0·8644	0·9053	0·9461
	I	0·1830	0·2277	0·2792	0·3380	0·4047	0·4794	0·5627	0·6555	0·7577	0·8701	0·9931
0·104	Z	0·2091	0·2429	0·2792	0·3182	0·3597	0·4037	0·4502	0·4994	0·5511	0·6053	0·6621
10	W	2·2175	2·3884	2·5592	2·7301	2·9010	3·0719	3·2428	3·4137	3·5846	3·7554	3·9265
S.W.G.	A	0·6522	0·7025	0·7527	0·8039	0·8533	0·9035	0·9538	1·0040	1·0543	1·1046	1·154
	I	0·2158	0·2694	0·3313	0·4019	0·4821	0·5720	0·6726	0·7843	0·9079	1·0439	1·1929
0·128	Z	0·2466	0·2874	0·3313	0·3783	0·4285	0·4817	0·5381	0·5976	0·6603	0·7262	0·7953

W = Weight in pounds per foot run. A = Cross-section area $\pi t(D - t)$. I = Moment of inertia $= \frac{\pi}{64}(D^4 - d^4)$.

Z = Modulus of resistance $= {}^{2I}/_{D} = \frac{A}{8}\left(\frac{D^2+d^2}{D}\right)$. D = Outside diameter. d = Inside diameter = D − 2t. t = Thickness.

Weights given are for steel tubes at 0·283 lbs. per cu. in. For duralumin multiply given weight by 0·361.
For aluminium multiply given weight by 0·328.

TABLE X.—WORKING LOADS FOR MILD STEEL RODS, WIRES, PINS, AND BOLTS, IN POUNDS.

Diam. in Inches	*Diam. in Millimetres.*	*Dead Load.*		*Load varying frequently from 0 to Max.*		*Load varying frequently from − Max. to + Max.*	
		Single Shear.	Tension.	Single Shear.	Tension.	Single Shear.	Tension.
$\frac{1}{32}$	0·79	8·5	9·2	4·9	6·3	2·4	3·1
$\frac{1}{16}$	1·58	33	39	21	27	10·5	13·5
$\frac{1}{8}$	3·17	134	158	85	109	42	54
$\frac{3}{16}$	4·76	304	358	193	248	96	124
$\frac{1}{4}$	6·34	540	635	343	440	170	220
$\frac{5}{16}$	7·93	840	995	537	690	270	350
$\frac{3}{8}$	9·52	1,210	1,430	772	990	390	500
$\frac{7}{16}$	11·10	1,650	1,950	1,050	1,250	530	630
$\frac{1}{2}$	12·70	2,160	2,550	1,375	1,770	690	890
$\frac{9}{16}$	14·30	2,740	3,230	1,740	2,230	870	1,120
$\frac{5}{8}$	15·90	3,380	3,980	2,150	2,760	1,080	1,380
$\frac{11}{16}$	17·50	4,080	4,730	2,600	3,340	1,300	1,670
$\frac{3}{4}$	19·00	4,850	5,730	3,090	3,970	1,550	1,990
$\frac{13}{16}$	20·60	5,700	6,740	3,630	4,660	1,820	2,330
$\frac{7}{8}$	22·20	6,600	7,800	4,210	5,410	2,110	2,710
$\frac{15}{16}$	23·80	7,600	9,000	4,830	6,210	2,420	3,110
1	25·40	8,650	10,400	5,500	7,960	2,750	3,530

TABLE XI.—BREAKING STRESSES OF WIRE WITH EQUIVALENTS IN TONS PER SQUARE INCH. (Wall.)

Milli-metres.	S.W.G.	Dec.	Area, Square Inch	120 Tons or 268,000 Pounds	115 Tons or 257,600 Pounds.	110 Tons or 246,400 Pounds	105 Tons or 235,200 Pounds	100 Tons or 224,000 Pounds	95 Tons or 212,800 Pounds	90 Tons or 201,600 Pounds	85 Tons or 190,400 Pounds	80 Tons or 179,200 Pounds	75 Tons or 168,000 Pounds	70 Tons or 156,800 Pounds
				Pounds	Pounds	Pounds	Pounds	Pounds	Pounds	Pounds	Pounds	Pounds	Pounds	Pounds.
4 064	8	0 160	0 020106	5,404	5,179	4·954	4,728	4,503	4 278	4 053	3,828	3,603	3,377	3,152
3·962	¼	0 156	0 019113	5,137	4,923	4,709	4,495	4,281	4,067	3,853	3,639	3,425	3,211	2,997
3·860	½	0·152	0 018145	4,877	4,674	4,471	4,267	4,064	3,861	3,658	3,454	3,251	3,048	2,845
3·759	¾	0·148	0 017203	4,624	4,431	4,238	4,046	3,853	3,660	3,468	3,275	3,082	2,890	2,697
3·658	9	0 144	0 016286	4,377	4,195	4,012	3,830	3,648	3 465	3,823	3,100	2,918	2,736	2,553
3·556	¼	0·140	0 015393	4,137	3,965	3,793	3,620	3,448	3,275	3,103	2,930	2,758	2,586	2,413
3·454	½	0 136	0 014526	3,904	3,742	3,579	3,416	3,254	3,091	2,928	2,765	2,603	2,440	2,277
3·352	¾	0 132	0 013684	3,678	3,525	3,372	3,218	3,065	2,912	2,758	2,605	2,452	2,299	2,145
3·251	10	0 128	0 012868	3,459	3,314	3,170	3,026	2,882	2,738	2,594	2 450	2,306	2,161	2,017
3·175	¼	0 125	0 012271	3,298	3,161	3,023	2,886	2 749	2,611	2,474	2,386	2,199	2,061	1,924
3·100	½	0 122	0·011689	3,142	3,011	2 880	2,749	2,618	2,487	2,356	2,225	2,094	1,964	1,833
3·022	¾	0·119	0 011122	2,989	2,865	2,740	2,615	2,491	2,366	2,242	2,117	1,993	1,868	1,744
2 946	11	0 116	0 010568	2,840	2,722	2,604	2,485	2,367	2,249	2 130	2,012	1,893	1,775	1,657
2·870	¼	0 113	0 010028	2,695	2,583	2,471	2,358	2,246	2,134	2,021	1,909	1,797	1,684	1,572
2·974	½	0·110	0 009503	2,554	2,448	2,341	2,235	2,129	2,022	1,915	1,809	1,703	1,596	1,490
2 717	¾	0·107	0·008992	2,417	2,316	2,215	2,115	2,014	1,913	1,812	1,712	1,611	1,510	1,410
2 642	12	0·104	0 008494	2,283	2,188	2,093	1,998	1,903	1,807	1,712	1,617	1,522	1,427	1,332
2 590		0 102	0 008171	2,196	2,105	2,013	1,921	1,830	1,738	1,647	1 555	1,464	1,372	1,281
2·5[illegible]5	¼	0 101	0·008011	2,153	2,063	1,974	1,884	1,794	1,705	1,615	1,525	1,435	1,346	1,256
2·540		0 100	0 007854	2,111	2,023	1,935	1,847	1 759	1,671	1,583	1,495	1,407	1,319	1,231
2 489	½	0 098	0·007543	2,027	1,943	1 858	1,774	1,690	1,605	1,520	1,436	1,407	1,267	1,182
2·438		0 096	0·007238	1,945	1,864	1 783	1,702	1,621	1,540	1,459	1,378	1,351	1,216	1,135
2·413	¾	0·095	0·007088	1,905	1,826	1,746	1,667	1,588	1,508	1,429	1,349	1,270	1,190	1,111
2·387		0 094	0 006939	1,865	1,787	1,710	1,632	1,554	1,476	1,399	1 321	1,243	1,165	1,088
2 337	13	0 092	0 006647	1,786	1,712	1,638	1,563	1,489	1,414	1,340	1,265	1,191	1,116	1,042
2·286		0·090	0 006361	1,710	1,638	1,567	1,496	1,425	1,353	1,282	1,211	1,140	1,068	997
2·260	¼	0·089	0 006221	1,672	1,602	1,532	1,463	1,393	1,323	1,254	1,184	1,114	1,045	975
2·235		0 088	0 006082	1,634	1,566	1,498	1,430	1,362	1,294	1,226	1,158	1,090	1,021	953
2·184	½	0·086	0 005808	1,561	1,496	1,431	1,366	1,301	1,236	1,171	1,106	1,041	2,975	910
2·133		0·084	0 005541	1,489	1,427	1,365	1,303	1,241	1,179	1,117	1,055	993	931	869
2·108	¾	0 083	0·005410	1,454	1,393	1,333	1,272	1,212	1,151	1,090	1,030	969	909	848
2·082		0 082	0 005281	1,419	1,360	1,301	1,242	1,183	1,123	1,064	1,005	946	887	828
2·032	14	0·080	0·005026	1,351	1,295	1,238	1,182	1,126	1,069	1,013	957	900	844	788
1·981	¼	0·078	0·004778	1,284	1,231	1,177	1,123	1,070	1,016	963	909	856	802	749
1·930	½	0 076	0·004536	1,219	1,168	1,117	1,066	1,016	965	914	863	813	762	711
1·879	¾	0·074	0·004300	1,156	1,107	1,059	1,011	963	915	867	818	770	722	674

BREAKING STRESSES OF WIRE WITH EQUIVALENTS IN TONS PER SQUARE INCH—*Continued.*

Milli-metres.	*S.W.G.*	*Dec.*	*Area, Square Inch.*	120 *Tons* *or* 268,000 *Pounds*	115 *Tons* *or* 257,600 *Pounds.*	110 *Tons* *or* 246,400 *Pounds.*	105 *Tons* *or* 235,200 *Pounds*	100 *Tons* *or* 224,000 *Pounds*	95 *Tons* *or* 212,800 *Pounds*	90 *Tons* *or* 201,600 *Pounds*	85 *Tons* *or* 190,400 *Pounds*	80 *Tons* *or* 179,200 *Pounds*	75 *Tons* *or* 168,000 *Pounds.*	70 *Tons* *or* 156·800 *Pounds.*
				Pounds.	*Pounds.*	*Pounds*	*Pounds*	*Pounds*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*
1·829	15	0·072	0·004071	1,094	1,048	1,003	957	912	866	820	755	729	684	638
1·778	¼	0·070	0·003848	1,034	991	948	905	862	819	775	752	689	646	603
1·727	½	0·068	0·003631	976	935	894	854	813	772	732	651	650	620	569
1·676	¾	0·066	0·003421	919	881	843	804	766	728	689	631	613	574	536
1·626	16	0·064	0·003217	864	828	792	756	720	684	648	612	576	540	504
1·574	¼	0·062	0·003019	811	777	744	710	676	642	608	574	541	507	473
1·524	½	0·060	0·002827	760	728	696	665	633	601	570	538	506	475	443
1·473	¾	0·058	0·002642	710	680	651	621	592	562	532	303	473	443	414
1·422	17	0·056	0·002463	662	634	606	579	552	524	496	469	441	413	386
1·371	¼	0·054	0·002290	615	590	564	538	513	487	461	436	410	384	359
1·320	½	0·052	0·002123	571	547	523	499	476	452	428	404	380	356	333
1·270	¾	0·050	0·001963	528	505	483	461	440	417	395	372	351	329	307
1·219	18	0·048	0·001809	486	466	445	425	405	385	364	344	324	304	283
1·168	¼	0·046	0·001661	446	428	409	390	372	353	335	316	297	279	260
1·117	½	0·044	0·001520	408	391	374	357	340	323	306	289	272	255	238
1·066	¾	0·042	0·001385	372	356	341	325	310	294	279	263	248	232	217
1·016	19	0·040	0·001256	337	323	309	295	281	267	253	239	225	211	197
0·990	¼	0·039	0·001194	321	307	294	281	267	254	240	227	214	200	187
0·965	½	0·038	0·001134	305	292	279	266	254	241	228	216	203	190	177
0·940	¾	0·037	0·001075	289	277	265	252	241	228	216	204	192	180	168
0·914	20	0·036	0·001017	273	262	250	239	228	216	205	193	182	171	159
0·889	¼	0·035	0·000962	258	247	237	226	215	204	194	183	172	161	150
0·863	½	0·034	0·000907	244	233	223	213	203	193	183	172	162	152	142
0·838	¾	0·033	0·000855	230	220	210	201	191	182	172	162	153	143	134
0·813	21	0·032	0·000804	216	207	198	189	180	171	162	153	144	135	126
0·787	¼	0·031	0·000754	202	194	186	177	169	160	152	143	135	126	118
0·762	½	0·030	0·000706	190	182	174	166	158	150	142	134	126	118	110
0·736	¾	0·029	0·000660	177	170	162	155	148	140	133	125	118	111	103
0·711	22	0·028	0·000615	165	158	151	144	138	131	124	117	110	103	96·5
0·600	½	0·026	0·000530	142	136	130	124	119	113	107	101	95	89	83·2
0·610	23	0·024	0·000452	121	111	111	106	101	96	91	86	81	76	70·9
0·584	½	0·023	0·000415	111	107	102	97	93	88	83·7	79	74·4	69·8	65·1
0·559	24	0·022	0·000380	102	98	93·6	89·4	85	80·9	76·6	72·3	68·1	83·8	59·6
0·533	½	0·021	0·000346	93	89	85·3	81·4	77·5	73·7	69·8	65·9	62	58·1	54·3
0·508	25	0·020	0·000314	84	81	77·4	73·9	70·3	66·8	63·3	59·8	56·3	52·7	49·2

TABLE XII.—SPECIFIC GRAVITY AND WEIGHT OF METALS.

Material.	*Specific Gravity.*	*Weight per Cub. Ft. in Lbs.*	*Weight per Cub. In. in Lbs.*
Duralumin	2·800	175·0	0·1015
Aluminium (rolled, sheet) ..	2·670	166·6	0·0960
„ (cast)	2·560	159·6	0·0920
Copper (sheet)	8·780	548·1	0·3160
„ (wire)	8·900	555·0	0·3210
Iron (cast)	7·230	451·0	0·2600
„ (wrought)	7·780	486·0	0·2800
Steel (mild)	7·852	489·6	0·2810
„ (cast)	7·848	489·3	0·2810
Brass (cast), average	8·280	517·0	0·2980
Gunmetal (10 copper to 1 tin) ..	8·464	528·4	0·3060
„ (8 copper to 1 tin) ..	8·459	528·0	0·3050
Tin (cast)..	7·291	455·0	0·2620
Zinc (cast)	7·000	437·0	0·2520
German silver	8·280	516·0	0·3000
Phosphor bronze (cast).. ..	8·600	536·8	0·3100
Aluminium bronze	7·680	475·0	0·2750

TABLE XIII.—STANDARD WIRE GAUGE: TABLE OF SIZES, WEIGHTS, AND LENGTHS OF STEEL WIRE.

Size on Standard Wire Gauge.	*Diameter.*		*Sectional Area in Square Inches.*	*Approximate Weight of—*		
	Decimal of an Inch.	Milli-metres		100 Feet.	Mile.	Kilometre.
				lbs.	lbs	lbs.
7/0	·5000	12·700	·1963500	66·700000	3,522	2,188
6/0	·4640	11·800	·1691000	57·440000	3,033	1,885
5/0	·4320	11·000	·1465700	49·790000	2,629	1,634
4/0	·4000	10·200	·1256800	42·690000	2,254	1,400
3/0	·3720	9·400	·1086900	36·930000	1,950	1,211
2/0	·3480	8·800	·0951000	32·310000	1,706	1,060
1/0	·3240	8·200	·0824400	28·010000	1,479	919
1	·3000	7·600	·0706900	24·010000	1,268	788
2	·2760	7·000	·0598200	20·320000	1,073	667
3	·2520	6·400	·0498700	16·850000	895	556
4	·2320	5·900	·0422700	14·360000	758	471
5	·2120	5·400	·0353000	12·000000	633	393
6	·1920	4·900	·0289600	9·810000	518	323
7	·1760	4·500	·0243200	8·260000	436	271
8	·1600	4·100	·0201100	6·820000	360	224
9	·1440	3·700	·0162800	5·530000	292	182
10	·1280	3·300	·0128700	4·370000	231	143
11	·1160	3·000	·0105700	3·600000	190	118
12	·1040	2·600	·0085000	2·880000	152	95
13	·0920	2·300	·0066500	2·250000	119	74
14	·0800	2·000	·0050300	1·700000	90	56
15	·0720	1·800	·0040700	1·380000	73	45
16	·0640	1·600	·0032200	1·100000	58	36
17	·0560	1·400	·0024600	0·830000	44	27·5000
18	·0480	1·200	·0018100	0·610000	32·500	20·2000
19	·0400	1·000	·0012600	0·420000	22·540	14·0000
20	·0360	0·900	·0010200	0·340000	18·250	11·3400
21	·0320	0·800	·0008000	0·273000	14·420	8·9600
22	·0280	0·700	·0006200	0·209000	11·040	6·8600
23	·0240	0·600	·0004500	0·154000	8·110	5·0400
24	·0220	0·550	·0003800	0·129000	6·820	4·2400
25	·0020	0·500	·0003100	0·107000	5·630	3·5000
26	·0180	0·450	·0002500	0·086000	4·560	2·8400
27	·0164	0·400	·0002100	0·072000	3·790	2·3500
28	·0148	0·370	·0001700	0·058000	3·090	1·9200
29	·0136	0·356	·0001400	0·050000	2·610	1·6200
30	·0124	0·320	·0001200	0·041000	2·170	1·3500

STANDARD WIRE GAUGE—*Continued.*

Size on Standard Wire Gauge.	*Diameter.*		*Sectional Area in Square Inches.*	*Approximate Weight of—*		
	Decimal of an Inch.	Millimetres.		100 Feet	Mile.	Kilometre.
				lbs.	lbs.	lbs.
31	·0116	0·280	·0001000	0·036000	1·890	1·1600
32	·0108	0·270	·0000910	0·031000	1·640	1·0200
33	·0100	0·254	·0000780	0·026000	1·400	0·8750
34	·0092	0·239	·0000660	0·022000	1·190	0·7440
35	·0084	0·203	·0000550	0·019000	0·901	0·5630
36	·0076	0·177	·0000450	0·015000	0·813	0·5080
37	·0068	0·172	·0000360	0·012000	0·651	0·4070
38	·0060	0·152	·0000280	0·009600	0·507	0·3170
39	·0052	0·127	·0000210	0·007200	0·380	0·2380
40	·0048	0·122	·0000180	0·006100	0·324	0·2020
41	·0044	0·112	·0000150	0·005100	0·272	0·1700
42	·0040	0·101	·0000120	0·004200	0·225	0·1400
43	·0036	0·091	·0000100	0·003400	0·182	0·1140
44	·0032	0·081	·0000080	0·002700	0·144	0·0900
45	·0028	0·071	·0000060	0·002100	0·110	0·0700
46	·0024	0·061	·0000040	0·001500	0·081	0·0500
47	·0020	0·050	·0000030	0·001060	0·056	0·0350
48	·0016	0·040	·0000020	0·000820	0·036	0·0225
49	·0012	0·030	·0000010	0·000266	0·020	0·0125
50	·0010	0·025	·0000007	0·000259	0·014	0·0097

TABLE XIV.—STRAINER WEIGHTS.

Diameter of Screw, over Thread, in Millimetres.	*Weight in Ounces.*	*Breaking Load in Pounds.*
2·5	0·125	480
3·0	0·200	700
3·5	0·400	1,000
4·0	0·600	1,180
4·5	1·000	1,515
5·0	2·000	1,900
6·0	2·660	2,315
7·0	3·750	3,680
8·0	5·750	4,670
10·0	6·500	7,530
12·0	8·660	11,000
14·0	13·250	15,200
16·0	14·250	19,970

TABLE XV.—WEIGHTS AND DIMENSIONS OF METAL SHEETS.

Standard Wire Gauge.	Thickness.		Weight: Lbs. per Square Foot.				
	Inch.	Millimetres.	Aluminium	Brass.	Copper.	Steel.	Tin.
	·375	9·525	5·180	16·70	17·10	15·00	14·40
3/0	·372	9·449	5·140	16·50	17·00	14·90	14·30
2/0	·348	8·839	4·810	15·50	15·90	13·90	13·40
1/0	·324	8·229	4·480	14·40	14·80	13·00	12·50
	·312	7·937	4·310	13·90	14·20	12·50	12·00
1	·300	7·620	4·150	13·30	13·70	12·00	11·50
	·289	7·341	3·990	12·90	13·20	11·60	11·10
	·278	7·061	3·840	12·40	12·70	11·10	10·70
2	·276	7·010	3·810	12·30	12·60	11·00	10·60
	·270	6·858	3·730	12·00	12·30	10·80	10·40
3	·252	6·401	3·480	11·20	11·50	10·10	9·68
	·250	6·350	3·450	11·10	11·40	10·00	9·60
	·238	6·045	3·290	10·60	10·90	9·52	9·14
4	·232	5·893	3·200	10·30	10·60	9·28	8·91
	·216	5·486	2·980	9·61	9·86	8·64	8·31
5	·212	5·385	2·930	9·43	9·68	8·48	8·14
	·200	5·080	2·760	8·90	9·12	8·00	7·68
6	·192	4·877	2·650	8·54	8·76	7·68	7·37
	·187	4·762	2·580	8·32	8·53	7·48	7·18
	·182	4·623	2·520	8·10	8·31	7·28	6·99
7	·176	4·470	2·430	7·83	8·03	7·05	6·70
	·166	4·216	2·290	7·38	7·58	6·64	6·37
8	·160	4·064	2·210	7·12	7·30	6·40	6·15
	·150	3·810	2·070	6·67	6·85	6·00	5·76
9	·144	3·658	1·990	6·41	6·57	5·76	5·53
	·136	3·454	1·880	6·05	6·20	5·44	5·22
10	·128	3·251	1·770	5·69	5·84	5·12	4·92
	·125	3·175	1·730	5·56	5·70	5·00	4·80
	·124	3·150	1·710	5·52	5·66	4·96	4·76
11	·116	2·946	1·600	5·16	5·29	4·64	4·46
	·112	2·845	1·550	4·98	5·11	4·48	4·30
12	·104	2·642	1·440	4·63	4·75	4·16	3·99
	·100	2·540	1·380	4·45	4·57	4·00	3·84
13	·092	2·337	1·270	4·09	4·20	3·68	3·53
	·090	2·286	1·240	4·00	4·11	3·60	3·46
	·082	2·082	1·130	3·65	3·75	3·28	3·15
14	·080	2·032	1·110	3·56	3·65	3·20	3·07
	·077	1·956	1·070	3·43	3·52	3·08	2·96
15	·072	1·829	0·995	3·20	3·29	2·88	2·77
	·068	1·727	0·940	3·02	3·11	2·72	2·61
	·065	1·651	0·898	2·89	2·97	2·60	2·50

WEIGHTS AND DIMENSIONS OF METAL SHEETS—*Continued.*

Standard Wire Gauge.	*Thickness.*		*Weight: Pounds per Square Foot.*				
	Inch	Millimetres	Aluminium.	Brass.	Copper	Steel.	Tin
16	·0640	1·626	·885	2·850	2·920	2·560	2·460
	·0630	1·600	·870	2·800	2·880	2·520	2·420
	·0620	1·587	·857	2·760	2·830	2·480	2·380
	·0600	1·524	·829	2·670	2·740	2·400	2·300
17	·0560	1·422	·774	2·490	2·560	2·240	2·150
	·0550	1·397	·760	2·450	2·510	2·200	2·110
	·0510	1·295	·705	2·270	2·330	2·040	1·960
18	·0480	1·219	·663	2·130	2·190	1·920	1·840
	·0470	1·194	·649	2·090	2·150	1·880	1·810
	·0420	1·067	·580	1·870	1·920	1·680	1·610
19	·0400	1·016	·552	1·780	1·830	1·600	1·540
	·0380	0·965	·525	1·690	1·740	1·520	1·460
20	·0360	0·914	·497	1·600	1·650	1·440	1·380
	·0350	0·889	·484	1·560	1·600	1·400	1·340
21	·0320	0·813	·442	1·420	1·460	1·280	1·230
	·0310	0·793	·429	1·380	1·420	1·240	1·190
22	·0280	0·711	·387	1·250	1·280	1·120	1·080
	·0270	0·686	·373	1·200	1·240	1·080	1·040
23	·0240	0·610	·332	1·070	1·100	0·960	0·921
	·0230	0·584	·318	1·020	1·050	0·920	0·883
24	·0220	0·559	·304	0·979	1·010	0·880	0·845
	·0210	0·533	·290	0·935	0·960	0·840	0·806
25	·0200	0·508	·276	0·890	0·914	0·800	0·768
	·0190	0·483	·262	0·846	0·868	0·760	0·730
26	·0180	0·457	·249	0·801	0·823	0·720	0·691
27	·0164	0·416	·227	0·730	0·750	0·656	0·630
	·0160	0·406	·221	0·712	0·731	0·640	0·614
	·0156	0·397	·215	0·694	0·713	0·624	0·599
28	·0148	0·376	·204	0·658	0·677	0·592	0·568
	·0140	0·356	·193	0·623	0·640	0·560	0·537
29	·0136	0·345	·188	0·605	0·622	0·544	0·522
30	·0124	0·315	·171	0·552	0·566	0·496	0·476
	·0120	0·305	·166	0·534	0·548	0·480	0·461
	·0105	0·267	·145	0·467	0·480	0·420	0·403
	·0090	0·229	·125	0·400	0·412	0·360	0·360
	·0080	0·203	·111	0·356	0·366	0·320	0·307
Specific gravity . .		. .	2·670	8·620	8·820	7·740	7·400
Ratio of weights		. .	1	3·230	3·300	2·900	2·780

TABLE XVI.—PRINCIPAL STANDARDS FOR WIRE GAUGE USED IN THE UNITED STATES: DIMENSIONS OF SIZES IN DECIMAL PARTS OF AN INCH.

Number of Wire Gauge.	*American, or Brown and Sharpe.*	*English, or Birmingham or Stubs'.*	*Washburn and Moen Manufacturing Co.*	*Number of Wire Gauge.*
000000	—	—	·4600	000000
00000	—	—	·4300	00000
0000	·460000	·454	·3930	0000
000	·409640	·425	·3620	000
00	·364800	·380	·3310	00
0	·324860	·340	·3070	0
1	·289300	·300	·2830	1
2	·257630	·284	·2630	2
3	·229420	·259	·2440	3
4	·204310	·238	·2250	4
5	·181940	·220	·2070	5
6	·162020	·203	·1920	6
7	·144280	·180	·1770	7
8	·128490	·165	·1620	8
9	·114430	·148	·1480	9
10	·101890	·134	·1350	10
11	·090742	·120	·1200	11
12	·080808	·109	·1050	12
13	·071961	·095	·0920	13
14	·064084	·083	·0800	14
15	·057068	·072	·0720	15
16	·050820	·065	·0630	16
17	·045257	·058	·0540	17
18	·040303	·049	·0470	18
19	·035890	·042	·0410	19
20	·031961	·035	·0350	20
21	·028462	·032	·0320	21
22	·025347	·028	·0280	22
23	·022571	·025	·0250	23
24	·020100	·022	·0230	24
25	·017900	·020	·0200	25
26	·015940	·018	·0180	26
27	·014195	·016	·0170	27
28	·012641	·014	·0160	28
29	·011257	·013	·0150	29
30	·010025	·012	·0140	30
31	·008928	·010	·0135	31
32	·007950	·009	·0130	32
33	·007080	·008	·0110	33
34	·006304	·007	·0100	34
35	·005614	·005	·0095	35
36	·005000	·004	·0090	36
37	·004453	—	·0085	37
38	·003965	—	·0080	38
39	·003531	—	·0075	39
40	·003144	—	·0070	40

INTERNATIONAL AIRCRAFT STANDARD BOARD SPECIFICATIONS (I.A.S.B.).

Specifications for Aircraft Ferrules and Thimbles.

General.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

Material.—2. Thimbles shall be manufactured of I.A.S.B. standard No. 1010 steel sheet, cold rolled and annealed. Ferrules shall be manufactured of the same steel as is used for the wire—namely, I.A.S.B. standard steels No. 1065, No. 1070, or No. 1080.

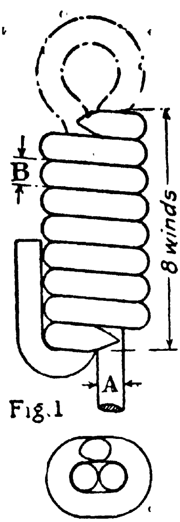


Fig. 1

Manufacture.—3. (*a*) Steel wire for winding into ferrules shall be uniformly coated with pure tin to solder readily.

(*b*) All thimbles shall be smoothly and evenly electro-galvanized.

Dimensions and Tolerances.—4. (*a*) Ferrules and thimbles shall conform within limits specified to the dimensions given in the tables and drawings.

(*b*) The manufacture shall provide hardened pin gauges for all sizes of thimbles and ferrules, and such gauges, after being approved by the Government, shall be used by the inspectors for determining all internal dimensions and shapes.

Delivery, Packing, and Shipping.—5. (*a*) Ferrules and thimbles shall be packed and shipped in fibre or pasteboard boxes containing 1,000 each.

(*b*) A label on each box shall be marked with order number or other distinguishing marks, size, material, evidence of inspection, etc., as required

Inspection and Rejection.—6. The inspector shall examine one sample taken at random from a box of 1,000 ferrules or thimbles and determine whether it conforms to these specifications.

TABLE XVII.—I.A.S.B. STANDARD TINNED STEEL AIRCRAFT FERRULES.

ENGLISH UNITS.

American Wire Gauge (B.S.).	*A and B.*	*D.*	*E.*	*Approximate Weight, 1000 Pieces.*
	Inch.	*Inch.*	*Inch.*	*Pounds.*
8	0·128	0·130	0·260	34·50
9	0·114	0·116	0·232	23·00
10	0·102	0·104	0·208	17·00
11	0·091	0·093	0·186	11·75
12	0·081	0·083	0·166	8·50
13	0·072	0·074	0·148	6·03
14	0·064	0·066	0·132	4·50
15	0·057	0·059	0·118	3·10
16	0·051	0·053	0·106	2·09

Fig. 2

METRIC UNITS.

American Wire Gauge (B.S.).	*A and B.*	*D.*	*E.*	*Approximate Weight, 1000 Pieces.*
	Mm.	*Mm.*	*Mm.*	*Kg.*
8	3·25	3·30	6·60	15·65
9	2·91	2·96	5·92	10·43
10	2·59	2·64	5·28	7·71
11	2·31	2·36	4·72	5·33
12	2·05	2·10	4·20	3·86
13	1·83	1·88	3·76	2·74
14	1·63	1·68	3·36	2·04
15	1·45	1·50	3·00	1·41
16	1·29	1·34	2·68	0·95

Table XVIII.—I.A.S.B. Standard Tinned Steel Aircraft Thimbles.

English Units.

Size.	*A.*	*B.*	*C.*	*D.*	*E.*	*Approximate Weight, 1000 Pieces.*
Inch.	*Inch.*	*Inches.*	*Inch.*	*Inch.*	*Inch.*	*Pounds.*
$\frac{1}{16}$ and $\frac{3}{32}$	0·35	0·70	0·07	0·09	0·032	3·00
$\frac{1}{8}$	0·35	0·70	0·07	0·13	0·032	4·34
$\frac{5}{32}$	0·40	0·80	0·10	0·17	0·032	6·36
$\frac{3}{16}$	0·50	1·00	0·135	0·21	0·032	9·00
$\frac{7}{32}$	0·60	1·20	0·15	0·24	0·032	13·50
$\frac{1}{4}$	0·70	1·40	0·17	0·25	0·032	16·63
$\frac{9}{32}$	0·80	1·60	0·198	0·30	0·040	30·36
$\frac{5}{16}$	0·90	1·80	0·21	0·33	0·040	33·00
$\frac{3}{8}$	1·00	2·00	0·26	0·39	0·060	74·00

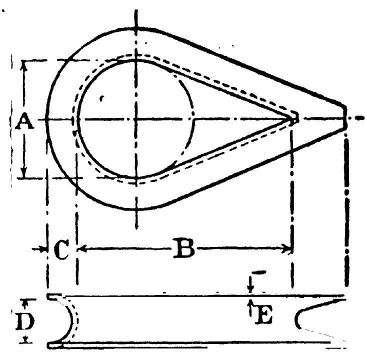


Fig. 3

Metric Units.

Size.	*A.*	*B.*	*C.*	*D.*	*E.*	*Approximate Weight, 1000 Pieces.*
Mm.	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Kg.*
1·59 and 2·38	8·89	17·78	1·78	2·29	0·81	1·36
3·18	8·89	17·78	1·78	3·30	0·81	1·97
3·97	10·16	20·32	2·54	4·32	0·81	2·88
4·76	12·70	25·40	3·43	5·33	0·81	4·08
5·56	15·24	30·48	3·81	6·10	0·81	6·12
6·35	17·78	35·36	4·32	6·35	0·81	7·54
7·14	20·32	40·64	5·03	7·62	1·02	13·77
7·94	22·86	45·72	5·33	8·38	1·02	14·97
9·53	25·40	50·80	6·60	9·91	1·52	33·57

Tolerance on dimension A (see Fig. 3) shall be + 0·01-inch (0·25 mm.).

TABLE XIX.—CHEMICAL COMPOSITION OF STANDARD CARBON STEELS.

Number.	*Carbon.*	*Manganese.*	*Phosphorus Maximum.*	*Sulphur Maximum.*
1065	0·60-0·70	0·50-0·70	0·04	0·045
1070	0·65-0·75	0·50-0·70.	0·04	0·045
1080	0·75-0·90	0·25-0·50	0·04	0·045

4P1.—I.A.S.B. Specifications for Turnbuckles.

General.—1. The general specifications, 1G1, shall form, according to their applicability, a part of these specifications.

Material.—2. Barrels shall be made of naval brass or equivalent alloy, I.A.S.B. specifications 3N4. The shank shall be made of steel, I.A.S.B. specifications 3S4.

Physical Properties and Tests.—3. (*a*) At least 2 per cent. of all turnbuckles shall be subjected to the test load given in the table and must withstand this test.

Steel turnbuckle shanks shall be heat treated to withstand the test loads specified.

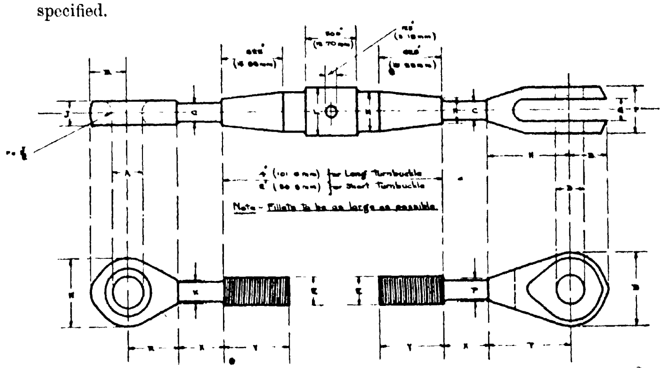


FIG. 4.—I.A.S.B. TURNBUCKLES.

(*b*) A bend test shall be made upon an (unbroken) shank of each turnbuckle tested in tension; the shank must withstand bending through 90° without cracking.

Dimensions and Tolerances.—4. Dimensions and tolerances are given in the tables following.

Assembly.—5. The threads are to be greased and must have a snug true fit allowing the barrel or shank to be turned by hand, and showing absolutely no slackness in fit or perceptible end shake when the ends have been extended three threads from the barrel.

Finish.—6. Turnbuckle shanks shall be thoroughly covered with a suitable non-corrosive grease before shipment. Before inspection of the finished turnbuckles they may, if so specified, be copper plated in order that initial stress in the barrel may be detected. After this inspection turnbuckles shall be greased or shall be coated with an air-drying enamel as specified.

TABLE XX.—I.A.S.B. SPECIFICATIONS FOR TURNBUCKLES.

DIMENSIONS IN INCHES.

I.A.S.B. No.	Strength in Pounds.	Eye End. C	Eye End. E	Eye End. X	Eye End. Y	Eye End. A	Eye End. B	Eye End. J	Eye End. K	Eye End. R	Eye End. W	Fork End. B	Fork End. D	Fork End. F	Fork End. G	Fork End. H	Fork End. P	Fork End. S	Barrel. T	Barrel. L	Barrel. M	Barrel. N	Threads per Inch U.S. Standard.
		+0·001 −0·002		+0·005 −0·005	+0·040 −0·000	+0·002 −0·000	+0·005 −0·005	+0·005 −0·002	+0·005 −0·005	+0·005 −0·005	+0·005 −0·005	+0·005 −0·005	+0·002 −0·000	+0·015 −0·000	+0·0015 −0·000	+0·005 −0·005	+0·005 −0·005	+0·005 −0·005	+0·005 −0·005	+0·005 −0·005	+0·005 −0·004	+0·005 −0·005	
1 A	1,500	0·130	0·203	0·500	0·500	0·219	0·250	0·188	0·219	0·281	0·500	0·275	0·156	0·313	0·110	0·300	0·219	0·500	0·560	0·375	0·281	0·208	30
1 B	1,500	0·130	0·203	1·531	0·500	0·219	0·250	0·188	0·219	0·281	0·500	0·275	0·156	0·313	0·110	0·300	0·219	0·500	0·560	0·375	0·281	0·208	30
1 C	1,500	0·130	0·203	0·500	0·500	0·219	0·250	0·188	0·219	0·281	0·500	—	—	—	—	—	—	—	—	0·375	0·281	0·208	30
1 D	1,300	0·130	0·205	1·531	0·500	0·219	0·250	0·188	0·219	0·281	0·500	—	—	—	—	—	—	—	—	0·375	0·281	0·208	30
2 A	2,150	0·157	0·203	0·500	0·563	0·219	0·328	0·188	0·219	0·313	0·500	0·328	0·188	0·313	0·110	0·438	0·219	0·500	0·625	0·375	0·328	0·281	30
2 B	2,150	0·157	0·203	1·531	0·563	0·219	0·328	0·188	0·219	0·313	0·500	0·328	0·188	0·313	0·110	0·500	0·219	0·500	0·687	0·375	0·328	0·281	30
2 C	2,150	0·157	0·203	0·500	0·563	0·219	0·328	0·188	0·219	0·313	0·500	*0·328	*0·188	—	—	—	—	—	—	0·375	0·328	0·281	30
2 D	2,150	0·157	0·203	1·531	0·563	0·219	0·328	0·188	0·219	0·313	0·500	—	—	—	—	—	—	—	—	0·375	0·328	0·281	30
3 A	3,000	0·185	0·234	0·500	0·625	0·281	0·391	0·219	0·250	0·375	0·625	0·391	0·250	0·344	0·110	0·625	0·250	0·625	0·813	0·453	0·391	0·313	28
3 B	3,000	0·185	0·234	1·375	0·625	0·281	0·391	0·219	0·250	0·406	0·625	0·391	0·250	0·344	0·110	0·625	0·250	0·625	0·813	0·453	0·391	0·313	28
3 C	3,000	0·185	0·234	0·500	0·625	0·281	0·391	0·219	0·250	0·375	0·625	*0·391	*0·250	—	—	—	—	—	—	0·453	0·371	0·313	28
3 D	3,000	0·185	0·234	1·375	0·625	0·281	0·391	0·219	0·250	0·406	0·625	—	—	—	—	—	—	—	—	0·453	0·391	0·313	28
4 A	4,000	0·213	0·265	0·500	0·688	0·344	0·422	0·250	0·281	0·500	0·688	0·422	0·250	0·438	0·203	0·625	0·281	0·688	0·875	0·500	0·438	0·375	26
4 B	4,000	0·213	0·265	1·250	0·688	0·344	0·422	0·250	0·281	0·500	0·688	0·422	0·250	0·438	0·203	0·625	0·281	0·688	0·875	0·500	0·438	0·375	26
4 C	4,000	0·213	0·265	0·500	0·688	0·344	0·422	0·250	0·281	0·500	0·688	—	—	—	—	—	—	—	—	0·500	0·438	0·375	26
4 D	4,000	0·213	0·265	1·250	0·688	0·344	0·422	0·250	0·281	0·500	0·688	—	—	—	—	—	—	—	—	0·500	0·438	0·375	26
5 A	5,750	0·256	0·313	0·500	0·750	0·313	0·469	0·281	0·313	0·563	0·750	0·469	0·281	0·563	0·203	0·625	0·313	0·750	0·875	0·531	0·484	0·438	24
5 B	5,750	0·256	0·313	1·250	0·750	0·313	0·469	0·281	0·313	0·563	0·750	0·469	0·281	0·563	0·203	0·625	0·313	0·750	0·875	0·531	0·484	0·438	24
5 C	5,750	0·256	0·313	0·500	0·750	0·313	0·469	0·281	0·313	0·563	0·750	—	—	—	—	—	—	—	—	0·531	0·484	0·438	24
5 D	5,750	0·256	0·313	1·250	0·750	0·313	0·469	0·281	0·313	0·563	0·750	—	—	—	—	—	—	—	—	0·531	0·484	0·438	24
6 A	8,400	0·318	0·375	0·500	0·875	0·313	0·500	0·328	0·375	0·625	0·875	0·500	0·313	0·563	0·266	0·563	0·375	0·875	0·875	0·625	0·594	0·469	22
6 B	8,400	0·318	0·375	1·125	0·875	0·313	0·500	0·328	0·375	0·625	0·875	0·500	0·313	0·563	0·266	0·563	0·375	0·875	0·875	0·625	0·594	0·469	22
6 C	8,400	0·318	0·375	0·500	0·875	†0·313	0·500	0·328	0·313	0·625	0·875	—	—	—	—	—	—	—	—	0·625	0·594	0·469	22
6 D	8,400	0·318	0·375	1·125	0·875	0·313	0·500	0·328	0·375	0·625	0·875	—	—	—	—	—	—	—	—	0·625	0·594	0·469	22

* When a turnbuckle has two eye ends with different size holes for the pin and cable, the two diameters are given.
† This turnbuckle is to be bored to receive pin on one end only.

Table XXI.—I.A.S.B. Specifications for Turnbuckles.

Dimensions in Millimetres.

I.A.S.B. No.	Strength in Kilograms	Eye End										Fork End								Barrel			Threads per Inch U S Standard.
		C	E	X	Y	A	B	J	K	R	W	B	D	F	G	H	P	S	T	L	M	N	
		+0·03 −0·05		+0·13 −0·13	+1·02 −0·00	+0·05 −0·00	+0·13 −0·13	+0·13 −0·05	+0·13 −0·13	+0·13 −0·13	+0·13 −0·13	+0·13 −0·13	+0·05 −0·00	+0·38 −0·00	+0·38 −0·00	+0·13 −0·13	+0·13 −0·13	+0·13 −0·13	+0·13 −0·13	+0·13 −0·13	+0·13 −0·13	+0·13 −0·13	
1 A	680·4	3·30	5·16	12·70	12·70	5·56	6·35	4·76	5·56	7·14	12·70	6·99	3·97	7·94	2·79	7·62	5·56	12·70	14·22	9·53	7·14	5·28	30
1 B	680·4	3·30	5·16	38·89	12·70	5·56	6·35	4·76	5·56	7·14	12·70	6·99	3·97	7·94	2·79	7·62	5·56	12·70	14·22	9·53	7·14	5·28	30
1 C	680·4	3·30	5·16	12·70	12·70	5·56	6·35	4·76	5·56	7·14	12·70	—	—	—	—	—	—	—	—	9·53	7·14	5·28	30
1 D	680·4	3·30	5·16	38·89	12·70	5·56	6·35	4·76	5·56	7·14	12·70	—	—	—	—	—	—	—	—	9·53	7·14	5·28	30
2 A	975·2	3·99	5·16	12·70	14·29	5·56	8·33	4·76	5·56	7·94	12·70	8·33	4·76	7·94	2·79	11·11	5·56	12·70	15·88	9·53	8·33	7·14	30
2 B	975·2	3·99	5·16	38·89	14·29	5·56	8·33	4·76	5·56	7·94	12·70	8·33	4·76	7·94	2·79	12·70	5·56	12·70	17·46	9·53	8·33	7·14	30
2 C	975·2	3·99	5·16	12·70	14·29	5·56	8·33	4·76	5·56	7·94	12·70	*8·33	*4·76	—	—	—	—	—	—	9·53	8·33	7·14	30
2 D	975·2	3·99	5·16	38·89	14·29	5·56	8·33	4·76	5·56	7·94	12·70	—	—	—	—	—	—	—	—	9·53	8·33	7·14	30
3 A	1,361	4·70	5·95	12·70	15·88	7·14	9·92	5·56	6·35	9·53	15·88	9·92	6·35	8·73	2·79	15·88	6·35	15·88	20·64	11·51	9·92	7·94	28
3 B	1,361	4·70	5·95	34·93	15·88	7·14	9·92	5·56	6·35	10·32	15·88	9·92	6·35	8·73	2·79	15·88	6·35	15·88	20·64	11·51	9·92	7·94	28
3 C	1,361	4·70	5·95	12·70	15·88	7·14	9·92	5·56	6·35	9·53	15·88	*9·92	*6·35	—	—	—	—	—	—	11·51	9·92	7·94	28
3 D	1,361	4·70	5·95	34·93	15·88	7·14	9·92	5·56	6·35	10·32	15·88	—	—	—	—	—	—	—	—	11·51	9·92	7·94	28
4 A	1,814	5·41	6·73	12·70	17·46	8·73	10·72	6·35	7·14	12·70	17·46	10·72	6·35	11·11	5·16	15·88	7·14	17·46	22·23	12·70	11·11	9·53	26
4 B	1,814	5·41	6·73	31·75	17·46	8·73	10·72	6·35	7·14	12·70	17·46	10·72	6·35	11·11	5·16	15·88	7·14	17·46	22·23	12·70	11·11	9·53	26
4 C	1,814	5·41	6·73	12·70	17·46	8·73	10·73	6·35	7·14	12·70	17·46	—	—	—	—	—	—	—	—	12·70	11·11	9·53	26
4 D	1,814	5·41	6·73	31·75	17·46	8·73	10·72	6·35	7·14	12·70	17·46	—	—	—	—	—	—	—	—	12·70	11·11	9·53	26
5 A	2,608	6·50	7·94	12·70	19·05	7·94	11·91	7·14	7·94	14·29	19·05	11·91	7·14	14·29	5·16	15·88	7·94	19·05	22·23	13·49	12·30	11·11	24
5 B	2,608	6·50	7·94	31·75	19·05	7·94	11·91	7·14	7·94	14·29	19·05	11·91	7·14	14·29	5·16	15·88	7·94	19·05	22·23	13·49	12·30	11·11	24
5 C	2,608	6·50	7·94	12·70	19·05	7·94	11·91	7·14	7·94	14·29	19·05	—	—	—	—	—	—	—	—	13·49	12·30	11·11	24
5 D	2,608	6·50	7·94	31·75	19·05	7·94	11·91	7·14	7·94	14·29	19·05	—	—	—	—	—	—	—	—	13·49	12·30	11·11	24
6 A	3,810	8·08	9·53	12·70	22·23	7·94	12·70	8·33	9·53	15·88	22·23	12·70	7·94	14·29	6·75	14·29	9·53	22·23	22·23	15·88	15·08	11·91	22
6 B	3,810	8·08	9·53	28·58	22·23	7·94	12·70	8·33	9·53	15·88	22·23	12·70	7·94	14·29	6·75	14·29	9·53	22·23	22·23	15·88	15·08	11·91	22
6 C	3,810	8·08	9·53	12·70	22·23	†7·94	12·70	8·33	9·53	15·88	22·23	—	—	—	—	—	—	—	—	15·88	15·08	11·91	22
6 D	3,810	8·08	9·53	28·58	22·23	7·94	12·70	8·33	9·53	15·88	22·23	—	—	—	—	—	—	—	—	15·88	15·08	11·91	22

* When a turnbuckle has two eye ends with different size holes for the pin and cable, the two diameters are given.

† This turnbuckle is to be bored to receive pin on one end only.

Note.—In column marked "I.A.S.B No" the letters used are for the following items: A, short fork and eye turnbuckle; B, long fork and eye turnbuckle; C, short double-eye turnbuckle; D, long double-eye turnbuckle.

TABLE XXII.—EQUIVALENT BREAKING STRESSES FOR STRAINERS AND TURNBUCKLES. (Ascol.)

Breaking Strains.	*A.G.S.* (R.A.F.).			*Admiralty.*			*Metric (approximate).*			"*Avro*" (*Barrelless*).			*Blackburn.*		
Lbs.	*No.*	*Diam.*	*Breaking Strain.*	*No.*	*Diam.*	*Breaking Strain.*	*No.*	*Diam.*	*Breaking Strain.*	*No.*	*Diam.*	*Breaking Strain.*	*No.*	*Diam.*	*Breaking Strain.*
		B.A.	*Lbs.*		*B.A.*	*Lbs.*		*Mm.*	*Lbs.*		*Mm.*	*Lbs.*		*B.A.*	*Lbs.*
600—750	138 L and 139 S	6	600	251	4	750	—	3	670	—	—	—	—	—	—
960—1288	140	4	1050	252	2	1288	—	3·5 4	960 1150	"C" & "D"	4	1216	1	4	1050
1450	—	—	—	—	—	—	—	4·5	1450	—	—	—	—	—	—
1850—1950	141 E and 142 S	2	1900	—	—	—	—	5	1850	"E" & "F"	5	1950	2	2	1900
2408—2800	—	—	—	253	B.S.F. $\frac{1}{4}$ *inch.*	2408	—	6	2800	—	—	—	—	—	—
3248—3808	143 L and 144 S	B.S.F. $\frac{1}{4}$ *inch*	3450	254 255	$\frac{9}{32}$ *inch* $\frac{5}{16}$ *inch*	3248 3808	—	7	3600	—	—	—	3	B.S.F. $\frac{1}{4}$ *inch*	3450
4650	145 L and 146 S	$\frac{9}{32}$ *inch*	4650	—	—	—	—	—	—	—	—	—	4	$\frac{9}{32}$ *inch*	4650
5500—5824	147	$\frac{5}{16}$ *inch*	5700	256	$\frac{3}{8}$ *inch*	5824	—	8	5500	—	—	—	5	$\frac{5}{16}$ *inch*	5700
7150—7436	148	$\frac{11}{32}$ *inch*	7150	—	—	—	—	10	7436	—	—	—	—	—	—
8064—8500	149	$\frac{3}{8}$ *inch*	8500	257	$\frac{7}{16}$ *inch*	8064	—	—	—	—	—	—	6	$\frac{3}{8}$ *inch*	8500
10640	—	—	—	258	$\frac{1}{2}$ *inch*	10640	—	—	—	—	—	—	—	—	—
11800	—	—	—	—	—	—	—	—	—	—	—	—	7	$\frac{7}{16}$ *inch*	11800
15500	—	—	—	—	—	—	—	—	—	—	—	—	8	$\frac{1}{2}$ *inch*	15500

APPENDIX III

AIR MINISTRY SPECIFICATIONS FOR FERROUS METALS

SPECIFICATION FOR NICKEL-CHROME STEEL AXLE TUBES.—AIR BOARD SPECIFICATION T. 2.

PROVISIONAL SPECIFICATION FOR 50-TON CARBON STEEL TUBES.—AIR BOARD SPECIFICATION T. 5.

SPECIFICATION FOR MILD STEEL TUBES.—AIR BOARD SPECIFICATIONS T. 6.

SCHEDULE OF STANDARD SIZES OF STEEL TUBES FOR AIRCRAFT.—AIR BOARD SPECIFICATIONS T. 10.

LIMITING LOADS FOR TUBULAR STEEL STRUTS.—AIR BOARD SPECIFICATION T. 6.

LIMITING LOADS FOR TUBULAR STEEL STRUTS.—AIR BOARD SPECIFICATION T. 6.

LIMITING LOADS FOR TUBULAR STEEL STRUTS.—AIR BOARD SPECIFICATION T. 6.

SUPPLEMENTARY SCHEDULE OF LARGER STANDARD SIZES OF ROUND STEEL TUBES FOR AIRCRAFT.—AIR BOARD SPECIFICATION T. 10.

OVAL STEEL TUBES FOR AIRCRAFT.—AIR BOARD SPECIFICATION T. 11.

SCHEDULE OF STANDARD SIZES OF STREAMLINE STEEL TUBES.—AIR BOARD SPECIFICATION T. 13.

SPECIFICATION FOR STREAMLINE WIRES.—AIR BOARD SPECIFICATION W. 3.

SPECIFICATION FOR SWAGED WIRES.—AIR BOARD SPECIFICATION W. 8.

SPECIFICATION FOR FLEXIBLE STEEL WIRE ROPE.—AIR BOARD SPECIFICATION 2 W. 2.

APPENDIX III

AIR MINISTRY SPECIFICATIONS FOR FERROUS METALS

Specification for Nickel-Chrome Steel Axle Tubes.—Air Board Specification T. 2.

NOTE.—*Axle tubes are seriously weakened where drilled.*

Accuracy of Form, Size, and Straightness.—(*a*) The tubes are to be accurately circular

(*b*) The mean outside diameter (*i e*, the mean between the maximum and minimum diameter) at any section is not to differ from the size shown in column 2 of the Schedule by more than $\pm 0{\cdot}005$ inch

(*c*) The ends of the tubes for a distance of 14 inches from each end are to be rounded by pressure, so that no diameter exceeds the nominal diameter (Col 1)

(*d*) No axle is to exceed the maximum specified weight (calculated by multiplying its length by the weight per foot given in column 5 of the Schedule)

(*e*) At no point in a tube is the thickness to fall short of the nominal thickness by more than 10 per cent or exceed it by more than 20 per cent.

(*f*) The tubes are to be as straight as possible, and in no part of the length is the departure from straightness to exceed one three-hundredth of the length of that part

Mechanical Tests.—(*a*) The tubes are to comply with the following tests ·

(*b*) *Proof Load* —Every axle is to be tested by having a proof bending moment applied to it near one end, and at least one axle in ten is to be tested in this way at both ends. The proof load is given in column 7 and the leverage L is given in column 8 of the Schedule at the end of this specification.

(*c*) *Tensile Test.*—One test piece to represent every 100 axles is to be cut from one of the tubes from which the axles have been cut; it is to be heat treated with the axles it represents and is then to be tested in tension; it must give the following results:

Ultimate tensile strength - - -	Not less than 85 tons per square inch.
Elongation on 2 inches - - -	,, ,, 5 per cent.
,, 4 ,, - - -	,, ,, 3 ,,

SCHEDULE.*

1	2	3		4	5	6	7	
Nominal Diam.	*True Outside Diam. (Lim. ± ·005 in.)*	*Thickness.*		*Min. Area of Section.*	*Max. Weight per Foot.*	*Modulus of Section Z.*	*Proof Load.*	*Proof Load Leverage L.*
Inches.	*Inches.*	*Gauge.*	*Inches*	*Inches.*^{2}	*Lb.*	*Inches.*^{3}	*Lb.*	*Inches.*
2·375	2·368	10	·128 −·000 +·010	·903	3·30	·482	2,410	35·0
2·165	2·158	10	·128 −·000 +·010	·819	3·00	·394	2,290	30·0
2·165	2·158	12	·104 −·000 +·008	·673	2·46	·331	1,930	30·0
2·165	2·158	14	·080 −·000 +·006	·524	1·92	·264	1,540	30·0
1·75	1·743	10	·128 −·000 +·010	·652	2·38	·247	1,730	25·0
1·75	1·743	12	·104 −·000 +·008	·538	1·97	·209	1,460	25·0
1·75	1·743	14	·080 −·000 +·006	·420	1·54	·168	1,170	25·0
1·75	1·743	16	·064 −·000 +·005	·339	1·24	·138	964	25·0
1·50	1·493	14	·080 −·000 +·006	·357	1·30	·120	966	21·7
1·50	1·493	16	·064 −·000 +·005	·289	1·05	·099	797	21·7
1·50	1·493	18	·048 −·000 +·004	·219	·80	·077	620	21·7
1·10	1·095	14	·080 −·000 +·006	·256	·93	·061	807	13·2

Provisional Specification for 50-Ton Carbon Steel Tubes.—Air Board Specification T. 5.

The tubes are to be delivered in the normalized condition. (Where brazed or welded their strength will be reduced to the value given in the softening test.)

General Condition.—The tubes are to be straight, smooth, true to section, of uniform sectional thickness, and of equal diameter throughout, free from scale, dirt specks, longitudinal seaming, lamination, grooving or blistering, both internally and externally.

Accuracy of Dimensions.—The mean diameter of any tube is not to differ from the size specified by more than ±0·002 inch.

The mean thickness of any tube is not to be less than the specified gauge, and is not to exceed it by more than 0·004 inch in tubes thinner than 0·08 inch, or by more than 5 per cent in thicker tubes. Any variation of thickness due to eccentricity of the bore is not to exceed 20 per cent. of the specified thickness.

Tests.—The tubes are to comply with the following mechanical tests:

Tension and Compression Tests.—A test piece consisting of a short length cut off the tube must give the following results, without further heat treatment or other manipulation.

Normalized Tubes:

Ultimate stress in tension not less than	50	tons per square inch.	
Yield point ,, ,, ,,	45	,,	,,
Yield point in compression ,,	45	,,	,,

Softening Test.—Additional tensile tests are to be made when required to prove that the tubes will not soften unduly when brazed or otherwise heated. For this purpose the test piece, before it is tested, is to be heated to a full red heat at one end, while the other end remains cold, and is then to be allowed to cool. When tested the ultimate strength is not to be less than 30 tons per square inch, and the yield point is not to be less than 18 tons per square inch.

Flattening Test.—A sample of the tube of length equal to its diameter is to be flattened till the sides are not more than eight times the thickness of the metal apart. The samples must stand this treatment without cracking.

Specification for Mild Steel Tubes.—Air Board Specification T. 6.

HARD DRAWN AND BLUED. CARBON ABOUT 0·15 PER CENT.

If blued tubes are annealed, brazed, or welded, their strength will be reduced at the parts where they are so treated to 20 tons per square inch ultimate and 11 tons per square inch yield point.

Tubes under ¾ inch outside diameter are difficult to make to this Specification, and should, unless strength is essential, be ordered to Specification for Softened Tubes.

General Condition.—The tubes are to be smooth, true to section, of uniform sectional thickness, and of equal diameter throughout, free from scale, dirt, specks, longitudinal seaming, lamination, grooving or blistering, both internally and externally.

Accuracy of Form, Size, and Straightness.—(*a*) Round tubes are to be accurately circular.

(*b*) The mean outside diameter (*i.e.*, the mean between the maximum and minimum diameter) at any point is not to differ from the size ordered by more than $\pm 0{\cdot}004$ inch (or for tubes over 2 inches diameter, by more than diameter/500). The mean inside diameter is not to be less than the correct outside diameter *minus* twice the maximum permissible thickness, nor greater than same *minus* twice the minimum permissible thickness.

(*c*) Oval tubes are to be of the correct form and dimensions within the tolerances specified in Schedule T. 11.

(*d*) No tube is to have a mean thickness less than the specified gauge, or exceeding it by more than 0·004 inch, except tubes thicker than 0·060 inch, for which the tolerance is to be 7½ per cent. of their thickness. (Tube

ordered to be 22-gauge thick are to be 0·025 inch with a tolerance of + 0·004 inch to agree with the dimensions set out in Schedule T., 10.)

(e) At no point in a tube is the thickness to fall short of the nominal thickness by more than 10 per cent. or exceed it by more than 15 per cent.

(f) The tubes are to be as straight as possible, and in no part of the length is the departure from straightness to exceed one six-hundredth of the length of that part.

Tests.—(a) The tubes are to comply with the following mechanical tests:

(b) *Tension and Compression Tests.*—Test pieces, consisting of short lengths cut off the tube, must give the following results, without further heat treatment or other manipulation:

Ultimate strength in tension	not	less	than	30	tons	per square inch.
Yield point	,,	,,	,,	28	,,	,,
Yield point in compression	,,	,,	,,	28	,,	,,

(c) *Flattening Test.*—The tube is to be flattened at the end, or at any point where defective material is suspected, by a few blows (not more than six), till the sides are not more than three times the thickness of the metal apart. The tubes must stand this treatment without cracking.

(d) *Crushing Test.*—Samples of the tube selected are to be crushed endwise until the outside diameter is increased in one zone by 25 per cent., or until one complete fold is formed. The samples must stand this treatment without cracking.

Schedule of Standard Sizes of Steel Tubes for Aircraft.—Air Board Specification T. 10.

(THIS SCHEDULE DOES NOT APPLY TO AXLE TUBES.)

17 GAUGE. Thickness 0·056 inch (Tolerance – 0, + 0·004 inch).

Nominal Size. Outside Diameter (Tolerance ±0·004 in.).	*Minimum Area of Section.*	*Maximum Weight per Foot.*	*Moment of Inertia I.*	*Modulus of Section Z.*
Inches.	*Inches.*^{2}	*Pounds.*	*Inches.*^{4}	*Inches.*^{3}
$\frac{1}{4}$	0·034	0·122	0·000174	0·00139
$\frac{5}{16}$	0·045	0·162	0·000384	0·00246
$\frac{3}{8}$	0·056	0·202	0·000736	0·00393
$\frac{7}{16}$	0·067	0·242	0·00125	0·00568
$\frac{1}{2}$	0·078	0·282	0·00196	0·00783
$\frac{5}{8}$	0·100	0·362	0·00409	0·0131
$\frac{3}{4}$	0·122	0·442	0·00740	0·0197
$\frac{7}{8}$	0·144	0·522	0·0121	0·0278
1	0·166	0·602	0·0186	0·0372
$1\frac{1}{8}$	0·188	0·683	0·0269	0·0479
$1\frac{1}{4}$	0·210	0·763	0·0375	0·0600
$1\frac{3}{8}$	0·232	0·843	0·0506	0·0735
$1\frac{1}{2}$	0·254	0·923	0·0663	0·0884
$1\frac{5}{8}$	0·276	1·00	0·0851	0·105
$1\frac{3}{4}$	0·298	1·08	0·107	0·122
$1\frac{7}{8}$	0·320	1·16	0·132	0·141
2	0·342	1·24	0·162	0·162
$2\frac{1}{8}$	0·364	1·32	0·195	0·183

20 GAUGE (Approx. 1 mm.). Thickness 0·036 inch (Tolerance – 0, + 0·004 inch).

Nominal Size. Outside Diameter (Tolerance ±0·004 in.).	*Minimum Area of Section.*	*Maximum Weight per Foot.*	*Moment of Inertia I.*	*Modulus of Section Z.*
Inches.	*Inches.*^{2}	*Pounds.*	*Inches.*^{4}	*Inches.*^{3}
$\frac{1}{4}$	0·0242	0·0897	0·000142	0·00114
$\frac{5}{16}$	0·0312	0·116	0·000305	0·00195
$\frac{3}{8}$	0·0383	0·143	0·000557	0·00297
$\frac{7}{16}$	0·0454	0·170	0·000923	0·00422
$\frac{1}{2}$	0·0525	0·197	0·00142	0·00568
$\frac{5}{8}$	0·0666	0·250	0·00290	0·00928
$\frac{3}{4}$	0·0808	0·303	0·00516	0·0138
$\frac{7}{8}$	0·0949	0·357	0·00836	0·0191
1	0·109	0·410	0·0127	0·0254
$1\frac{1}{8}$	0·123	0·464	0·0183	0·0325
$1\frac{1}{4}$	0·137	0·517	0·0253	0·0405
$1\frac{3}{8}$	0·151	0·570	0·0340	0·0494
$1\frac{1}{2}$	0·166	0·624	0·0444	0·0592
$1\frac{5}{8}$	0·180	0·677	0·0567	0·0698
$1\frac{3}{4}$	0·194	0·731	0·0712	0·0814
$1\frac{7}{8}$	0·208	0·784	0·0880	0·0938
2	0·222	0·837	0·107	0·107
$2\frac{1}{8}$	0·236	0·891	0·129	0·121

Approximately 22 GAUGE. Thickness 0·025 inch (Tolerance – 0, + 0·004 inch).

$\frac{1}{4}$	0·0177	0·0685	0·000113	0·000905
$\frac{5}{16}$	0·0226	0·0878	0·000234	0·00150
$\frac{3}{8}$	0·0275	0·107	0·000423	0·00226
$\frac{7}{16}$	0·0324	0·127	0·000693	0·00317
$\frac{1}{2}$	0·0373	0·146	0·00106	0·00422
$\frac{5}{8}$	0·0471	0·185	0·00212	0·00680
$\frac{3}{4}$	0·0569	0·223	0·00375	0·00999
$\frac{7}{8}$	0·0668	0·162	0·00605	0·0138
1	0·0766	0·301	0·00911	0·0182
$1\frac{1}{8}$	0·0864	0·339	0·0131	0·0233
$1\frac{1}{4}$	0·0962	0·378	0·0181	0·0289
$1\frac{3}{8}$	0·106	0·417	0·0242	0·0351
$1\frac{1}{2}$	0·116	0·456	0·0315	0·0420
$1\frac{5}{8}$	0·126	0·494	0·0403	0·0495
$1\frac{3}{4}$	0·135	0·533	0·0504	0·0576
$1\frac{7}{8}$	0·145	0·572	0·0622	0·0663
2	0·155	0·610	0·0759	0·0756
$2\frac{1}{8}$	0·165	0·649	0·0909	0·0855

Extra Tubes for Sockets Only.

Approximately 22 Gauge. Thickness 0·025 inch (Tolerance – 0, + 0·005 inch.

Outside Diameter.	*To Take*	*Minimum Area.*	*Maximum Weight per Foot.*	*Outside Diameter.*	*To Take*	*Minimum Area.*	*Maximum Weight per Foot.*
Inches.	*Inches.*	*Inches.*^{2}	*Pounds.*	*Inches.*	*Inches.*	*Inches.*^{2}	*Pounds.*
$\frac{9}{16}$	$\frac{1}{2}$	0·042	0·166	$1\frac{7}{16}$	$1\frac{3}{8}$	0·111	0·437
$\frac{11}{16}$	$\frac{5}{8}$	0·052	0·204	$1\frac{9}{16}$	$1\frac{1}{2}$	0·120	0·460
$\frac{13}{16}$	$\frac{3}{4}$	0·062	0·244	$1\frac{11}{16}$	$1\frac{5}{8}$	0·130	0·515
$\frac{15}{16}$	$\frac{7}{8}$	0·071	0·282	$1\frac{13}{16}$	$1\frac{3}{4}$	0·140	0·554
$1\frac{1}{16}$	1	0·081	0·321	$1\frac{15}{16}$	$1\frac{7}{8}$	0·150	0·592
$1\frac{3}{16}$	$1\frac{1}{8}$	0·091	0·360	$2\frac{1}{16}$	2	0·160	0·631
$1\frac{5}{16}$	$1\frac{1}{4}$	0·102	0·405				

1. **The Areas, Moments of Inertia, and Moduli (bending)** are calculated for tubes of the minimum thickness—*i e* , 0·65 inch for 17 gauge tubes, 0·036 inch for 20 gauge tubes, and 0·025 inch for 22 gauge tubes.

2. **The Weights per Foot** are calculated for tubes of the maximum thickness—*i e* , 0·060 inch for 17 gauge tubes, 0·040 inch for 20 gauge tubes, and 0·029 inch for 22 gauge tubes The weight is taken to be 490 lb per cubic foot

3 **Telescopic Tubes.**—The 17 gauge tubes (omitting the $\frac{5}{16}$ and $\frac{7}{16}$ sizes) form a telescopic series, each fitting over the next size, $\frac{1}{8}$ inch smaller in diameter

The 22 gauge tubes (with the socket sizes) also form a telescopic series, each fitting over the next size $\frac{1}{16}$ inch smaller in diameter

4. **Tubes for Struts.**—Strut tubes are carefully straightened and then blued, but to avoid bending during handling they must not be ordered in lengths exceeding 10 to 12 feet.

5. **Tubes for General Purposes.**—These are treated in the same way as strut tubes. Long tubes for boundary edges and similar purposes can be made much straighter if built up of shorter pieces, and should be ordered in lengths not exceeding 10 feet

6 **Tubes for Sockets.**—The 17 gauge and 22 gauge tubes may be used for sockets (*see* Clause 3), and also tubes of the special standard thickness given below. Additional sizes are provided in the table headed *Tubes for Sockets.* Tubes for use as sockets are more readily obtainable than strut tubes, because strut tubes have to be carefully straightened and more accurately heat treated; orders should therefore always state when tubes are intended only for sockets. Such tubes must not be used for carrying loads

Tubes for use as sockets should not be ordered in lengths exceeding 4 feet; if the lengths they are going to be cut into are specified, the tubes will be

supplied in multiples of these lengths; if not they will be supplied in random lengths of 4 feet and under.

7. **Special Standard Thicknesses.**

No. 1. Special $0{\cdot}090^{-0}_{+0{\cdot}007}$—fits over a tube $\frac{3}{16}$ inch smaller in O.D.

,, 2. ,, $0{\cdot}120^{-0}_{+0{\cdot}009}$,, ,, $\frac{1}{4}$,, ,,

,, 3. ,, $0{\cdot}150^{-0}_{+0{\cdot}011}$,, ,, $\frac{5}{16}$,, ,,

8. **Tolerances and Fits.**—The tolerances specified give an average clearance between tube and socket of about 0·008 inch.

9. **Orders.**—Orders for standard tubes must state if they are for *struts* or *sockets.*

If they are for *struts* the order must give for each tube—

(*a*) Number of tubes and length of each, *or* Total length and lengths in which it is to be used.

(*b*) Outside diameters and thicknesses or gauges.

(*c*) Specification number, which defines the quality of the steel.

If the tubes are for *sockets* the order must give—

(*d*) Total length required, and when practicable, the lengths the tubes are going to be cut into, so that exact multiples may be supplied.

(*e*) Outside diameters and sizes they are to take

(*f*) Specification number.

Example—Supply 1,000 strut tubes 5 feet 6 inches long, 1 inch diameter, 17 gauge, *or* Supply 6,500 feet of 1 inch diameter, 17 gauge tube for cutting into 5 feet 6 inch lengths.

Also supply 100 feet of socket tubing $1\frac{1}{8}$ inch O D. to take 1 inch, for cutting into 9 inch pieces.

10. **Strength of Struts.**—The curves on pp. 705, 706, and 707, give the limiting loads for struts of any length made of any of the standard sizes of steel tubes.

Allowance is made for the maximum crookedness and eccentricity of bore which is permitted in the Air Board Specifications.

The *Limiting Load* given by the curves is the load which makes the maximum stress in the tube equal to the yield point—*i.e.*, to 28 tons per square inch.

The *Collapsing Load* of a strut is either the same as, or a little higher than, the limiting load.

Limiting Loads for Tubular Steel Struts.—Air. Board Specification T. 6.

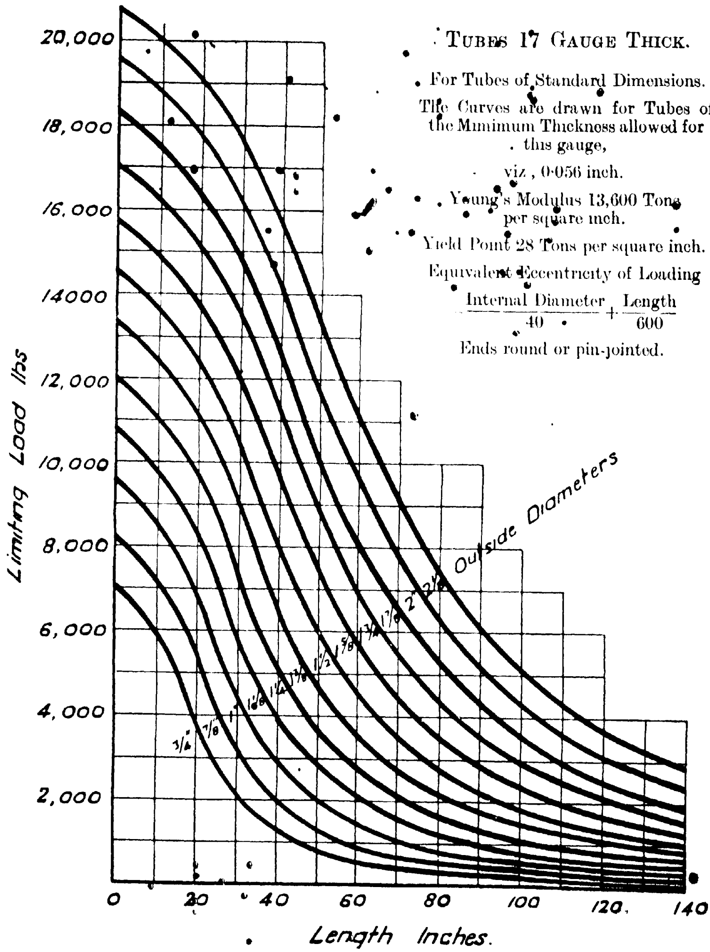


FIG. 1.

Limiting Loads for Tubular Steel Struts.—Air Board Specification T. 6.

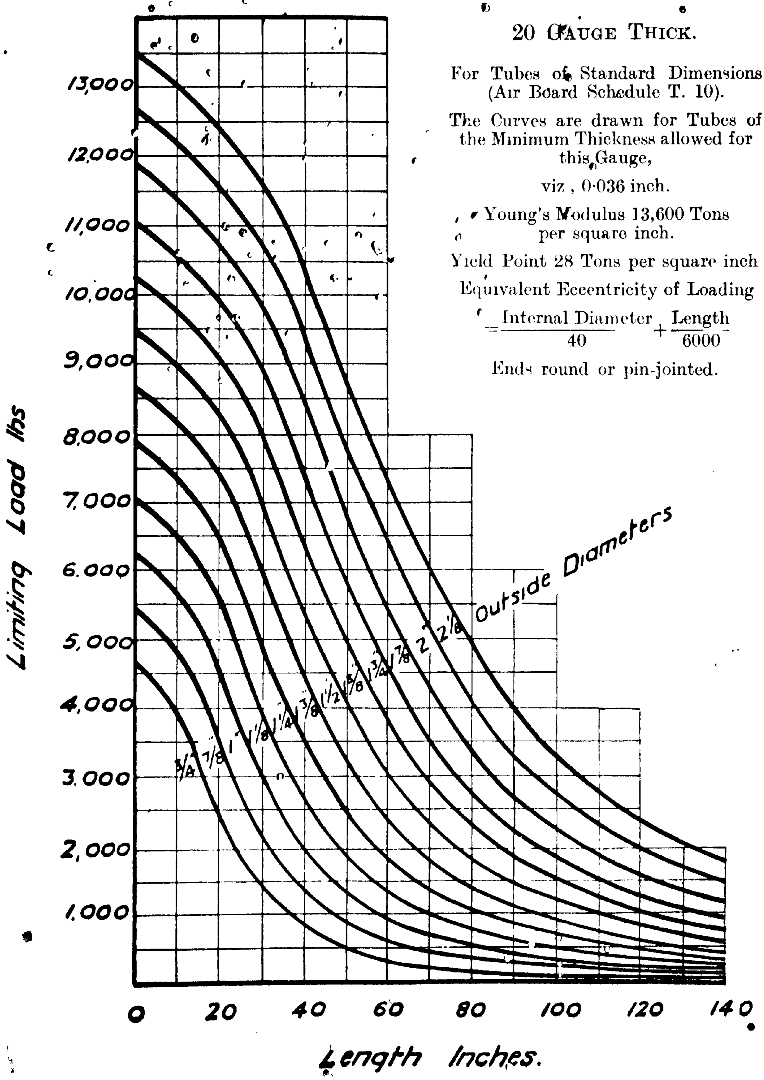


FIG. 2.

Limiting Loads for Tubular Steel Struts.—Air Board Specification T. 6.

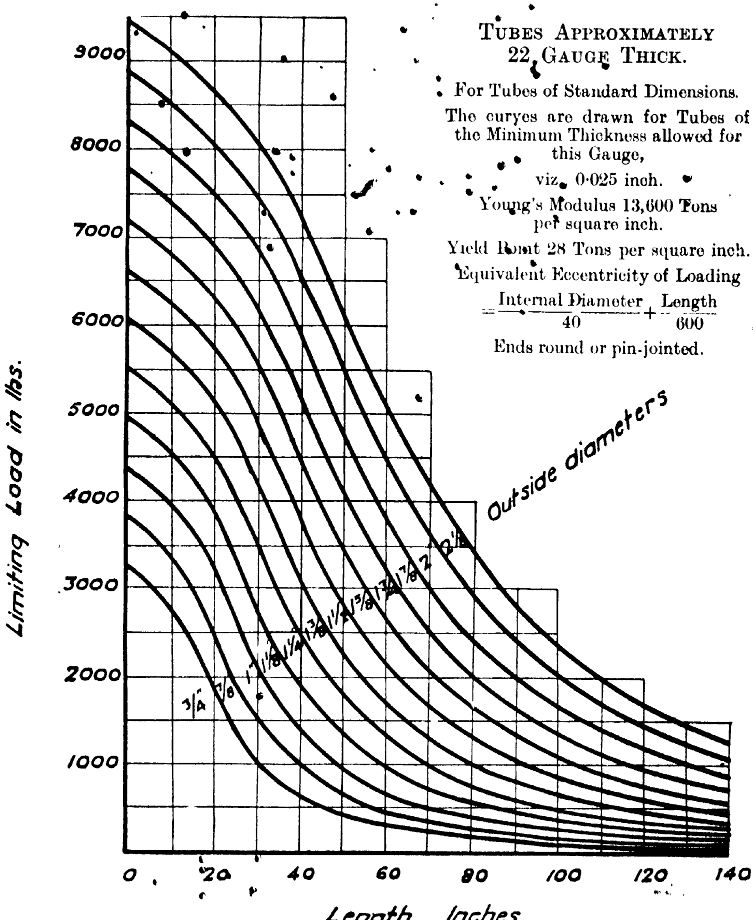


FIG. 3.

Supplementary Schedule of Larger Standard Sizes of Round Steel Tubes for Aircraft.—Air Board Specification T. 10.

TUBES FOR STRUTS, STRAIGHTENED AND NORMALIZED.

Approximately 11 GAUGE. Thickness 0·118 inch min. to 0·122 inch max.

Outside Diameter (Tolerance ±0·004 in.).	To Take.	Minimum Area of Section (see Note).	Maximum Weight per Foot (see Note).	Radius of Gyration (see Note).
Inches.	*Inches.*	*Square Inches.*	*Pounds.*	*Inches.*
2¼	2	0·790	2·779	0·753
2½	2¼	0·883	3·105	0·841
2¾	2½	0·976	3·431	0·930
3	2¾	1·068	3·757	1·018
3¼	3	1·161	4·083	1·106
3½	3¼	1·955	4·409	1·950
3¾	3½	1·347	4·735	1·283
4	3¾	1·439	5·061	1·371
4¼	4	1·532	5·387	1·460
4½	4¼	1·625	5·713	1·548
4¾	4½	1·717	6·039	1·636
5	4¾	1·810	6·365	1·725

Approximately 17 GAUGE. Thickness 0·056 inch min. to 0·060 inch max.

2¼	2⅛	0·386	1·407	0·774
2⅜	2¼	0·408	1 487	0·818
2½	2⅜	0·430	1·567	0·862
2⅝	2½	0·452	1·647	0·907
2¾	2⅝	0·474	1·727	0·951
2⅞	2¾	0·496	0·808	0·995
3	2⅞	0·518	1·888	1·039
3⅛	3	0·540	1·968	1·083
3¼	3⅛	0·562	2·048	1·128
3⅜	3¼	0·584	2·128	1·172
3½	3⅜	0·606	2·208	1·216
3⅝	3½	0·628	2·288	1·260
3¾	3⅝	0·650	2·369	1·304
3⅞	3¾	0·672	2·449	1·348
4	3⅞	0·694	2·529	1·393
4⅛	4	0·716	2·609	1·437
2¼	4⅛	0·738	2·689	1·481
4⅜	4¼	0·760	2·769	1·525
4½	4⅜	0·782	2·850	1·569
4⅝	4½	0·804	2·930	1·614
4¾	4⅝	0·826	3·010	1·658
4⅞	4¾	0·848	3·090	1·702
5	4⅞	0·870	3·170	1·746

Approximately 20 GAUGE. Thickness about 1 mm., from 0·036 inch min. to 0·040 inch max.

Outside Diameter (Tolerance ±0·004 in.).	*To Take*	*Minimum Area of Section (see Note).*	*Maximum Weight per Foot (see Note).*	*Radius of Gyration (see Note).*
Inches.	*Inches.*	*Square Inches.*	*Pounds.*	*Inches.*
2¼	—	0·250	0·946	0·781
2½	—	0·278	1·053	0·869
2¾	—	0·307	1·160	0·958
3	—	0·335	1·267	1·046
3¼	—	0·363	1·374	1·135
3½	—	0·392	1·481	1·223

Approximately 22 GAUGE. Thickness 0·025 inch min. to 0·029 inch max.

2¼	2 3/16	0·174	0·689	0·785
2⅜	2 5/16	0·184	0·748	0·829
2½	2 7/16	0·194	0·767	0·873
2⅝	2 9/16	0·204	0·806	0·917
2¾	2 11/16	0·214	0·844	0·962
2⅞	2 13/16	0·224	0·883	1·006
3	2 15/16	0·233	0·922	1·050

EXTRA TUBES FOR SOCKETS ONLY.

Approximately 22 GAUGE. Thickness 0·025 inch min. to 0·029 inch max.

2 3/16	2⅛	0·169	0·670	—
2 5/16	2¼	0·179	0·709	—
2 7/16	2⅜	0·189	0·747	—
2 9/16	2½	0·199	0·786	—
2 11/16	2⅝	0·209	0·825	—
2 13/16	2¾	0·209	0·864	—
2 15/16	2⅞	0·228	0·902	—
3 1/16	3	0·238	0·941	—

NOTE.—Sectional areas are calculated for tubes of minimum thickness, viz., 0·118, 0·056, 0·036, and 0·025 inch respectively.

Weights per foot are calculated for maximum thickness, viz., 0·122, 0·060, 0·040, and 0·029 inch respectively.

Radii of gyration are calculated for minimum diameter and thickness.

Sockets.—All the tubes except those of 20 gauge may be used as sockets for other standard tubes.

Struts.—Curve A (Fig. 4) gives the limiting stress, and hence the limiting load, for a tubular strut of any size and length, allowing for the crookedness and eccentricity of bore allowed in the Air Board Tube Specifications.

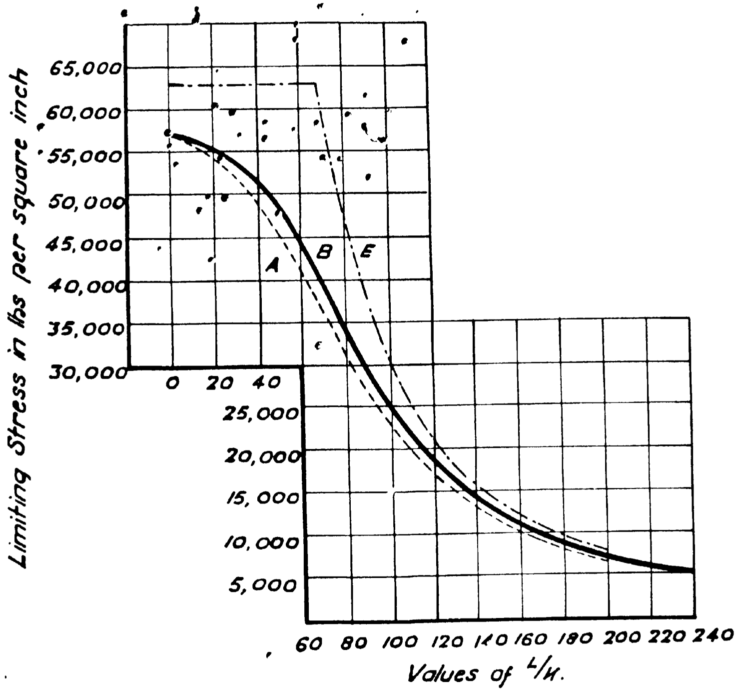


FIG. 4.

Specially Straight Tubes.—The tubes in this schedule can be supplied, when so ordered, with a deviation from straightness not exceeding one-half the amount allowed in the Tube Specifications. Curve B (Fig. 4) gives the limiting stress, and hence the limiting load, for struts of any size and length allowing for this reduced crookedness and the eccentricity of bore allowed in the Air Board Specifications.

Oval Steel Tubes for Aircraft.—Air Board Specification T. 11. (See Fig. 5.)

SCHEDULES OF STANDARD SIZES AND PROPERTIES OF SECTIONS.

Outside Diameters. B. Tolerance $\pm \frac{1}{2}$ per Cent. of B.	Outside Diameters. D. Tolerance ± 1 per Cent. of D.	Minimum Area of Section (See Note 1)	Weight per Ft. Run of Tube of Maximum Section (See Note 2).	Radii of Gyration (See Note 1). About Axis XX.	Radii of Gyration (See Note 1). About Axis YY.	Moduli of Section (See Note 1). About Axis XX.	Moduli of Section (See Note 1). About Axis YY.	Limiting Bending Loads at 10 Inches Overhang (See Note 3 and Fig. 6). Wx.	Limiting Bending Loads at 10 Inches Overhang (See Note 3 and Fig. 6). Wy.
Ins.	*Ins.*	*Sq. Ins.*	*Lb.*	*Ins.*	*Ins*	*Ins*^{3}	*Ins.*^{3}	*Lb.*	*Lb.*
				17 Gauge. Thickness, 0·056 inch to 0·060 inch.					
1	·4	·120	·436	·298	·132	0214	·0105	132	66
1¼	·5	·151	·556	·377	·170	·0344	·0176	216	110
1½	·6	·184	·673	·455	208	·0513	·0268	321	168
1¾	·7	·217	·791	534	·246	·0711	0379	446	238
2	·8	·249	·910	·613	·284	0943	0509	592	319
2¼	·9	·282	1·028	·692	·322	·1204	·0659	756	412
2½	1 0	·314	1·147	·771	·361	·1503	·0827	943	518
				20 Gauge Thickness, 0·036 inch to 0 040 inch.					
1	·4	·079	·299	·304	139	·0147	0077	92	48
1¼	·5	·100	·378	·383	177	·0236	0127	148	80
1½	·6	·121	·457	·462	·216	·0345	·0189	217	118
1¾	·7	·142	·536	·541	·254	0476	·0264	299	165
2	8	·163	·616	619	·292	·0628	·0350	394	220
2¼	·9	·184	·695	·698	·330	·0800	·0449	502	282
2½	1·0	·205	·774	·777	·368	·0994	·0562	623	352
				Approximately 22 Gauge. Thickness, 0·025 inch to 0·029 inch.					
⅝	·25	·0341	·134	189	·086	·0039	·0020	24	13
¾	·3	·0413	·163	·228	·105	·0058	·0031	36	19
1	·4	·0559	·220	·307	·143	·0106	·0058	67	36
1¼	·5	·0704	·278	·386	·181	·0169	·0094	106	59
1½	·6	·0849	·335	·465	·220	·0246	·0138	154	86
1¾	·7	·0996	·392	·544	·258	·0338	·0191	212	119
2	·8	·1140	·450	·623	·296	·0444	·0250	278	156

1 **The Areas, Radii of Gyration, and Moduli** are calculated for tubes of the minimum thickness—*i e*, 0 056 inch for 17 gauge tubes, 0·036 inch for 20 gauge tubes, and 0·025 inch for 22 gauge tubes.

2 **The Weights per Foot** are calculated for tubes of the maximum thickness—*i e*, 0·060 inch for 17 gauge tubes, 0·040 inch for 20 gauge tubes, and 0·029 inch for 22 gauge tubes.

Allowance has been made in each case for the tolerances.

3. **The Limiting Bending Loads** are the loads which, at an overhang of 10 inches (see Fig. 6), will produce a maximum fibre stress of 28 tons per

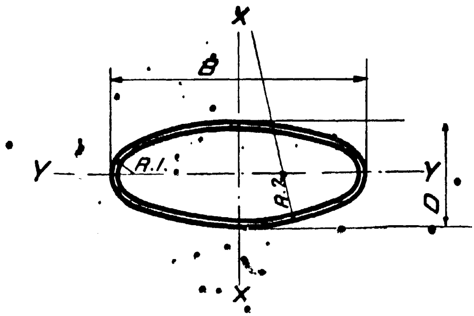


FIG. 5.—$2\frac{1}{2}$: 1 Oval.

$B = 2{\cdot}5\ D$ or $D = 0{\cdot}4\ B$.
$R_1 = 0{\cdot}3\ D$ or $0{\cdot}12\ B$ $R_2 = 1{\cdot}1\ B$ (approx.)
Area of Cross Section $= 1{\cdot}66(b+d)t$
Radius of Gyration about $XX = 0{\cdot}317b$
" " " $YY = 0{\cdot}386d$
Where $b = B - t$ and $d = D - t$ and $t =$ thickness.

square inch, which is the minimum yield stress allowed in Specification T 6. The limiting loads are calculated for tubes of the minimum section.

4. **Specification.**—Oval tubes should be ordered to Specification T. 1 or T. 6. They are straightened and normalized They should not be ordered in lengths exceeding 10 feet

Long tubes for trailing edges and similar purposes can be made straighter if built up of shorter pieces, and should be ordered in lengths not exceeding 10 feet

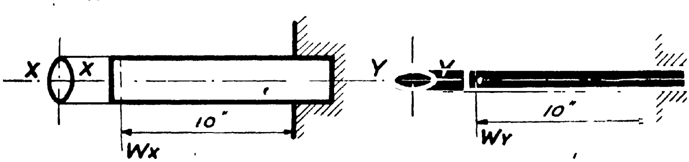


FIG. 6.

5. **Sockets.**—Properly formed socket tubes for all standard ovals can be obtained from the tube makers. These socket tubes are $\frac{1}{16}$ inch larger in each outside diameter than the tubes they are to go over; they will therefore be an easy fit when made 20 gauge thick and a close fit when made 18 gauge thick. Unless specially ordered in stated lengths the socket tubes may be supplied in lengths of about 6 inches.

Satisfactory sockets can be made by pressing round tubes into the proper shape. The inside diameter of the round tube should be three-quarters of the larger diameter B of the oval it has to fit.

6. **Struts.**—Fig. 7 gives the limiting stress, and hence the limiting load, for an oval strut of any size and length, allowing for crookedness and eccentricity of bore permitted in the A.B. Tube Specifications.

LIMITING STRESS FOR OVAL TUBULAR STEEL STRUTS WITH ROUND OR PIN-JOINTED ENDS.

Yield point of steel - - - 28 tons per square inch.
Young's Modulus, E - - - 13,600 ,, ,,

L = Length of strut in inches.
K = Radius of gyration of cross section of oval about the axis YY.
(See Table, p. 711).

Limiting load = limiting stress × area of cross section.

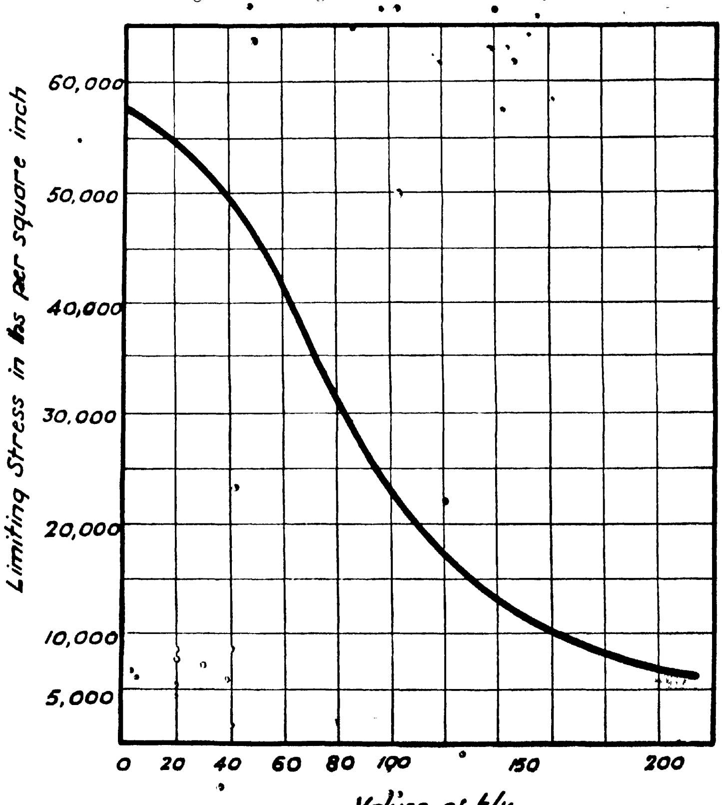


FIG. 7.

Schedule of Standard Sizes of Streamline Steel Tubes.— Air Board Specification T. 13.

STREAMLINE STEEL TUBES FOR AIRCRAFT.

(See Fig. 8.).

DIMENSIONS OF STANDARD SIZES.

Standard Streamline.	B. Maximum External Diameter. Tolerance $\pm\frac{1}{2}$ per Cent.	D. Minimum External Diameter. Tolerance ± 1 per Cent.	C. Centre of Gravity Below Nose.	R 1. External Radii.	R 2.	R 3.	R 4.	External Diameter of Equivalent Round Tube.
No	Inches	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.
1	3·4	1·175	1·628	7·637	2·350	0·540	0·242	2·463
2	$3\frac{1}{8}$	1·080	0·495	7·020	2·160	0·497	0·222	2·267
3 and 5	$2\frac{3}{4}$	0·950	1·316	6·175	1·900	0·437	0·196	1·995
4 and 6	2	0·691	0·957	4·485	1·381	0·318	0·142	1·450

PROPERTIES OF STANDARD SIZES.

Mean Thickness, $0{\cdot}056 \begin{smallmatrix} -0{\cdot}0 \\ +0{\cdot}004 \end{smallmatrix}$ inch.

Standard Streamline.	Minimum Area of Section.	Weight per Ft. Maximum Section.	Radii of Gyration. About XX.	Radii of Gyration. About YY.	Modulus. About XX.	Modulus. About YY.	Moment of Inertia. About XX.	Moment of Inertia. About YY.
No.	Inches.^{2}	Lb.	Inches.	Inches.	Inches.^{3}	Inches.^{3}	Inches.^{4}	Inches.^{4}
1	0·4235	1·540	1·045	0·426	0·261	0·131	0·4624	0·0769
2	0·389	1·412	0·960	0·390	0·2196	0·1094	0·3580	0·0591
3	0·341	1·239	0·842	0·340	0·1685	0·0829	0·2415	0·0394
4	0·245	0·890	0·608	0·241	0·0868	0·0414	0·0906	0·0143
	Mean thickness, $0{\cdot}036 \begin{smallmatrix} -0{\cdot}0 \\ +0{\cdot}004 \end{smallmatrix}$ inch.							
5	0·2213	0·8335	0·847	0·348	0·1108	0·0566	0·1590	0·0268
6	0·1599	0·602	0·613	0·249	0·0576	0·0287	0·0601	0·0099

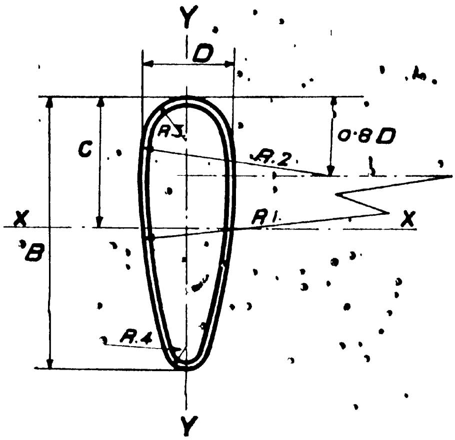


Fig 8.

Round tubing properly faired weighs less, and has a less wind resistance per foot, than streamline steel tubing of equal strength; the use of streamline tubing is permissible only when greater stiffness is required about one axis than the other, or it effects considerable simplification of connexions and details.

1 **The Areas, Radii of Gyration, Moments of Inertia, and Moduli** are calculated for tubes of the minimum thickness—*i e*, 0·056 inch and 0·036 inch.

2 **The Weights per Foot** are calculated for tubes of the maximum thickness *i e*, 0·060 inch and 0·040 inch

3 **Specification.**—Tubes should be ordered to Specification T 1 They will be straightened and blued in accordance with that specification They should not be ordered in lengths exceeding 10 feet

4 **Sockets.**—(*a*) Properly formed socket tubes for all standard streamline tubes may be obtained from the tube makers Standard sockets are made of 0·056 inch tube, and are made an easy fit over the standard tubes. Unless specially ordered in stated lengths, the socket tubes may be supplied in lengths of about 6 inches

(*b*) Socket tubes will be known as "Streamline socket SS 1" to fit streamline tube No 1; "Streamline socket SS 2" to fit streamline tube No. 2, etc. Socket tubes will comply with specification T 26 specially ordered otherwise

(*c*) Satisfactory sockets can be made by pressing round tubes into the proper shape. The inside diameter of the round tube should be slightly greater than the "equivalent round" of the streamline tube

Specification for Streamline Wires.—Air Board Specification W. 3.

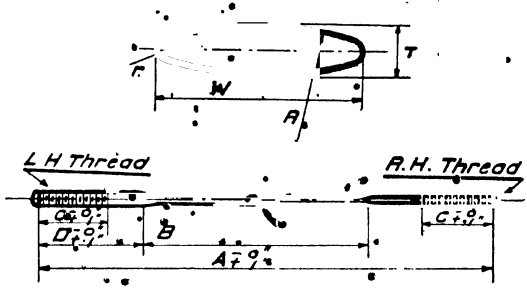


FIG. 9.

Size.	*Thread.*	*W Inch.*	*T Inch.*	*R Inch.*	*r Inch.*	*Area Square Inch.*	*Strength Pounds.*
4 B.A.	4 B.A.	0·192	0·048	0·288	0·011	0·0071	1050
2 B.A.	2 B.A.	0·256	0·064	0·384	0·014	0·0125	1900
$\frac{1}{4}$ in. B.S.F.	$\frac{1}{4}$ in. B.S.F.	0·348	0·087	0·522	0·019	0·0234	3450
$\frac{9}{32}$ in. B.S.F.	$\frac{9}{32}$ in. B.S.F.	0·404	0·101	0·606	0·022	0·0313	4650
$\frac{5}{16}$ in. B.S.F.	$\frac{5}{16}$ in. B.S.F.	0·440	0·110	0·660	0·024	0·0376	5700
$\frac{11}{32}$ in. B.S.F.	$\frac{11}{32}$ in. B.S.F.	0·496	0·124	0·744	0·027	0·0475	7150
$\frac{3}{8}$ in. B.S.F.	$\frac{3}{8}$ in. B.S.F.	0·540	0·135	0·810	0·030	0·0563	8500
$\frac{13}{32}$ in. B.S.F.	$\frac{13}{32}$ in. B.S.F.	0·596	0·149	0·894	0·033	0·0682	10,250
$\frac{7}{16}$ in. B.S.F.	$\frac{7}{16}$ in. B.S.F.	0·636	0·159	0·954	0·035	0·0781	11,800
$\frac{15}{32}$ in. B.S.F.	$\frac{15}{32}$ in. B.S.F.	0·692	0·173	1·038	0·038	0·0921	13,800
$\frac{1}{2}$ in. B.S.F.	$\frac{1}{2}$ in. B.S.F.	0·732	0·183	1·098	0·040	0·1026	15,500
$\frac{9}{16}$ in. B.S.F.	$\frac{9}{16}$ in. B.S.F.	0·836	0·209	1·254	0·045	0·1354	20,200
$\frac{5}{8}$ in. B.S.F.	$\frac{5}{8}$ in. B.S.F.	0·924	0·231	1·386	0·050	0·1655	24,700

The cross-sectional area of the wire is not to be less than that given in the table and is not to exceed it by more than $7\frac{1}{2}$ per cent. The sectional area may be assumed to be $0{\cdot}769\ W \times T$ where W and T are the diameters of the oval (see Fig. 9), or may be ascertained by weighing a length of the wire. The weight per foot run of wire of 0·1 square inch section is to be taken as 0·34 lb.

Tests.—The blanks are to comply with the following mechanical tests:

(*a*) *Tensile Tests.*—A test piece, cut off one end of the wire selected for testing so as to include the round end, must show an ultimate stress not less than the value given in the table accompanying this specification. The test piece is to be held at one end by the round part so that the shoulder between the round and oval parts is included in the part under stress.

(*b*) *Tensile Tests on Screwed End.*—The round end of the blank selected for testing is to be cut off, and is to be screwed with a pair of screwing dies so

that it is a good fit in an approved gauge. It is to be fitted with fork ends or with nuts, by which the load can be applied, and is then to be subjected to a tensile test, which must give an ultimate load not less than that obtained from the oval section of the blank from which it was cut. Where there are difficulties in screwing the pieces, temporary permission may be granted to substitute a test on unscrewed pieces for some of these tests.

(c) *Bending Test.*—Two samples cut from the wire selected for testing are to be subjected to the following bending test. One of the samples is to be cut from the end of the wire, so as to include the shoulder, and the test is to be applied so that the sample is bent at the shoulder, the sample being held by the oval part. The other sample is to be bent in the oval part. The sample is to be fixed in a vice which has the inner edges of the jaws rounded to a radius equal to three times the thickness of the wire given in the table. The projecting end of the wire is then to be bent at right angles to the fixed part, first to one side, then to the other, for a number of times till it breaks. Both samples must stand without breaking the number of bends specified in tests on swaged wires, each through 180°. The first bend through 90° is not counted.

Specification for Swaged Wires.—Air Board Specification W. 8.

Size.	*Thread.*	*Area.*	*Strength.*
		Square Inch.	*Pounds.*
4 B A.	4 B A.	0·0085	1050
2 B A.	2 B A	0·0129	1900
$\frac{1}{4}$ in. B S.F.	$\frac{1}{4}$ in. B S.F.	0·0230	3450
$\frac{9}{32}$ in. B.S.F.	$\frac{9}{32}$ in. B.S.F.	0·0337	4650
$\frac{5}{16}$ in. B S F.	$\frac{5}{16}$ in. B S.F.	0·0390	5700
$\frac{3}{8}$ in. B S.F.	$\frac{3}{8}$ in. B.S.F.	0·0590	8500
$\frac{7}{16}$ in. B S.F.	$\frac{7}{16}$ in. B.S.F	0·0835	11,800
$\frac{1}{2}$ in. B.S.F.	$\frac{1}{2}$ in. B.S.F.	0·1120	15,500

Mechanical Tests.—The following tests are to be carried out:

(a) *Tensile Test.*—A sample is to be cut from every coil, and when tested in tension must give the following results:

For wire rods of sizes from 4 BA to $\frac{11}{32}$ inch inclusive.	Ult. stress not less than 55 tons per square inch, or more than 65 tons per square inch.
For wire rods of sizes from $\frac{3}{8}$ inch to $\frac{1}{2}$ inch inclusive.	Ult. stress not less than 52 tons per square inch, or more than 62 tons per square inch.

(b) *Bending Test.*—A sample is to be cut from every coil and subjected to the following bending test:

The sample is to be fixed in a vice, or between dies, of which the inner edges are rounded to a radius equal to three times the diameter of the wire. The

projecting end is then to be bent at right angles to the fixed part, and is then to be bent backwards and forwards through an angle of 180° till it breaks. The wire must stand without breaking the following number of bends through 180° (the first bend through 90° is not counted):

For wires of sizes—

4 BA and 2 BA	Minimum number of bends, 6.
$\frac{1}{4}$ in., $\frac{9}{32}$ in., and $\frac{5}{16}$ in.	„ „ „ 5.
$\frac{11}{32}$ in., $\frac{3}{8}$ in., and $\frac{13}{32}$ in.	„ „ „ 4.
$\frac{7}{16}$ in. and upwards	„ „ „ 3.

Specification for Flexible Steel Wire Rope.—Air Board Specification 2 W. 2.

SCHEDULE.

EXTRA FLEXIBLE ROPES.

Item.	*Minimum Breaking Strength.*	*Maximum Diameter.*	*Construction.*	*Weight of 100 Feet.*
	Cwt.	*Inch.*		*Pounds.*
0	5	0·075	4 × 7	1·0
1	10	0·115	4 × 19	2·0
2	15	0·137	„	3·2
3	20	0·150	7 × 19	3·8
51	25	0·168	7 × 19	5·0
52	35	0·195	„	6·4
53	45	0·228	„	9·0
54	60	0·262	„	11·7
55	70	0·270	„	12·4
56	80	0·305	„	15·1
57	100	0·349	„	19·6
58	120	0·378	7 × 27	22·5
59	140	0·388	„	25·5
60	160	0·418	7 × 37	28·9
		STANDARD STRAINING CORDS.		
41	10	0·085	1 × 19	1·6
42	15	0·105	„	2·3
43	20	0·125	„	3·4
44	25	0·143	„	4·3
45	35	0·161	1 × 37	5·5
46	45	0·189	„	7·5
47	60	0·210	„	9·3
48	75	0·238	„	11·9
49	90	0·259	„	14·1

Tests on Wires.—The following tests are to be carried out:

(*a*) *Tensile Strength.*—A sample from each coil of wire is to be tested in tension. The ultimate tensile strength must be not more than 135 tons per

square inch, and not less than a value to be specified by the manufacturer of the wire rope.

(b) *Torsion Test.*—A sample from each coil of wire is to be tested in torsion. The wire is to be twisted in a torsion machine until it breaks. It must stand before breaking a number of turns not less than the number given by the formula:

Number of turns $=27.5$ per length of $100d$ for all wires up to and including 0.018 inch diameter

Number of turns $=20$ per length of $100d$ for larger wires.

Where d=the diameter of the wire in inches

(c) All wires showing a tendency to brittleness are to be rejected

Tests on Ropes.—The following tests on the rope are to be carried out:

(a) *A Tensile Test* is to be made on a sample cut from each piece of rope and must give at least the specified breaking load. The length of the sample tested is to be not less than six times the circumference of the rope, and in no case less than 15 inches in the clear between the points of security. The load is to be gradually applied till the sample breaks.

(b) Should the test pieces fail to reach the specified load, the rope represented by the test piece is to be rejected. Should, however, any wire break before 50 per cent. of the specified load has been applied, a re-test may be taken. No further re-test will be allowed, and should the re-test fail at any load less than that specified the rope represented by the test piece will be rejected.

(c) *A Bending Test* is to be made on a sample cut from each piece of rope. Each sample must be bent once round its own part and straightened again at least twenty times in succession without any of the wires breaking or the rope opening up.

APPENDIX IV

SOCIETY OF AUTOMOTIVE ENGINEERS' SPECIFICATIONS FOR CARBON AND ALLOY STEELS AND HEAT TREATMENTS

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SOCIETY OF AUTOMOTIVE ENGINEERS' SPECIFICATIONS FOR CARBON AND ALLOY STEELS AND HEAT TREATMENTS

TABLE I.—SOCIETY OF AUTOMOTIVE ENGINEERS (S.A.E.) STEEL SPECIFICATIONS.

Specification Number.	*Carbon per Cent.*	*Manganese per Cent.*	*Phosphorus* per Cent.*	*Sulphur* per Cent.*	*Nickel per Cent.*	*Chromium per Cent.*	*Vanadium† per Cent.*
1010	0·05–0·15	0·30–0·60	0·045	0·05	—	—	—
1020	0·15–0·25	0·30–0·60	0·045	0·05	—	—	—
1025	0·20–0·30	0·50–0·80	0·045	0·05	—	—	—
1035	0·30–0·40	0·50–0·80	0·045	0·05	—	—	—
1045	0·40–0·50	0·50–0·80	0·045	0·05	—	—	—
1095	0·90–1·05	0·25–0·50	0·04	0·05	—	—	—
‡1114	0·08–0·20	0·30–0·80	0·12	0·06–0·12	—	—	—
			NICKEL AND NICKEL CHROME STEELS.				
2315	0·10–0·20	0·50–0·80	0·04	0·05	3·25–3·75	—	—
2320	0·15–0·25	0·50–0·80	0·04	0·045	3·25–3·75	—	—
2330	0·25–0·35	0·50–0·80	0·04	0·045	3·25–3·75	—	—
2335	0·30–0·40	0·50–0·80	0·04	0·045	3·25–3·75	—	—
2340	0·35–0·45	0·50–0·80	0·04	0·045	3·25–3·75	—	—
2345	0·40–0·50	0·50–0·80	0·04	0·045	3·25–3·75	—	—
3120	0·15–0·25	0·50–0·80	0·04	0·045	1·00–1·50	0·45–0·75	—
3125	0·20–0·30	0·50–0·80	0·04	0·045	1·00–1·50	0·45–0·75	—
3130	0·25–0·35	0·50–0·80	0·04	0·045	1·00–1·50	0·45–0·75	—
3135	0·30–0·40	0·50–0·80	0·04	0·045	1·00–1·50	0·45–0·75	—
3140	0·35–0·45	0·50–0·80	0·04	0·045	1·00–1·50	0·45–0·75	—
3220	0·15–0·25	0·30–0·60	0·04	0·04	1·50–2·00	0·90–1·25	—
3230	0·25–0·35	0·30–0·60	0·04	0·04	1·50–2·00	0·90–1·25	—
3240	0·35–0·45	0·30–0·60	0·04	0·04	1·50–2·00	0·90–1·25	—
3250	0·45–0·55	0·30–0·60	0·04	0·04	1·50–2·00	0·90–1·25	—
*3315	0·10–0·20	0·45–0·75	0·04	0·04	2·75–3·25	0·60–0·95	—
*3335	0·30–0·40	0·45–0·75	0·04	0·04	2·75–3·25	0·60–0·95	—
*3350	0·45–0·55	0·45–0·75	0·04	0·04	2·75–3·25	0·60–0·95	—
3320	0·15–0·25	0·30–0·60	0·04	0·04	3·25–3·75	1·25–1·75	—
3330	0·25–0·35	0·30–0·60	0·04	0·04	3·25–3·75	1·25–1·75	—
3340	0·35–0·45	0·30–0·60	0·04	0·04	3·25–3·75	1·25–1·75	—

* Not to exceed. † Not less than.

‡ Screw stock; the amount of sulphur in this case is to be between the limits given.

SOCIETY OF AUTOMOTIVE ENGINEERS (S.A.E.) STEEL SPECIFICATIONS—*Continued.*

CHROME STEELS.

Specification Number.	*Carbon per Cent.*	*Manganese per Cent.*	*Phosphorus* per Cent.*	*Sulphur* per Cent.*	*Nickel per Cent.*	*Chromium per Cent.*	*Vanadium† per Cent.*
5120	0·15–0·25	‡	0·04	0·045	—	0·65–0·85	—
5140	0·35–0·45	‡	0·04	0·045	—	0·65–0·85	—
5165	0·60–0·70	‡	0·04	0·045	—	0·65–0·85	—
5195	0·90–1·05	0·20–0·45	0·03	0·03	—	0·90–1·10	—
51120	1·10–1·30	0·20–0·45	0·03	0·03	—	0·90–1·10	—
5295	0·90–1·05	0·20–0·45	0·03	0·03	—	1·10–1·30	—
52120	1·10–1·30	0·20–0·45	0·03	0·03	—	1·10–1·30	—

VANADIUM STEELS.

Specification Number.	*Carbon per Cent.*	*Manganese per Cent.*	*Phosphorus* per Cent.*	*Sulphur* per Cent.*	*Nickel per Cent.*	*Chromium per Cent.*	*Vanadium† per Cent.*
6120	0·15–0·25	0·50–0·80	0·04	0·04	—	0·80–1·10	0·15
6125	0·20–0·30	0·50–0·80	0·04	0·04	—	0·80–1·10	0·15
6130	0·25–0·35	0·50–0·80	0·04	0·04	—	0·80–1·10	0·15
6135	0·30–0·40	0·50–0·80	0·04	0·04	—	0·80–1·10	0·15
6140	0·35–0·45	0·50–0·80	0·04	0·04	—	0·80–1·10	0·15
6145	0·40–0·50	0·50–0·80	0·04	0·04	—	0·80–1·10	0·15
6150	0·45–0·55	0·50–0·80	0·04	0·04	—	0·80–1·10	0·15
6195	0·90–1·05	0·20–0·45	0·03	0·03	—	0·80–1·10	0·15

SILICO-MANGANESE STEELS.

Specification Number.	*Carbon per Cent.*	*Manganese per Cent.*	*Phosphorus* per Cent.*	*Sulphur* per Cent.*			
9250	0·45–0·55	0·60–0·80	0·045	0·045	1·80–2·10 per cent. Silicon.		
9260	0·55–0·65	0·50–0·70	0·045	0·045	1·50–1·80 ,, ,,		

TABLE II.—S.A.E. STEEL SPECIFICATIONS.

List of Heat Treatments.

A.—After forging or machining carbonize at between 1600° to 1750° F. (1650° to 1700° F. desired), cool slowly, or quench, reheat to 1450° to 1500° F., and quench.

B.—After forging or machining carbonize at betweer 1600° and 1700° F. (1650° to 1700° F. desired), cool slowly in the carbonizing medium, reheat to 1550° to 1625° F., quench, reheat to 1400° to 1450° F., quench, draw in hot oil at from 300° to 450° F., depending upon the hardness desired.

D.—After forging or machining heat to 1500° to 1600° F., quench, reheat to 1450° to 1500° F., quench, reheat to 600° to 1200° F., and cool slowly.

* Not to exceed. † Not less than.

‡ Two types of steel are available in this class—viz., one with manganese 0·25 to 0·50 per cent., and silicon not over 0·20 per cent.; the other with manganese 0·60 to 0·80 per cent., and silicon 0·15 to 0·50 per cent.

E.—After forging or machining heat to 1500° to 1550° F., cool slowly, reheat to 1450° to 1500° F., quench, and reheat to 600° to 1200° F., and cool slowly.

F.—After shaping or coiling heat to 1425° to 1475° F., quench in oil, reheat to 400° to 900° F., in accordance with degree of temper desired, and cool slowly.

G.—Carbonize at between 1600° and 1750° F. (1650° to 1700° F. desired), cool slowly in the carbonizing material, reheat to 1500° to 1550° F. and quench, reheat to 1300° to 1400° F., quench, reheat to 250° to 500° F. (in accordance with the necessities of the case), and cool slowly.

H.—After forging or machining heat to 1500° to 1600° F., quench, reheat to 600° to 1200° F., and cool slowly.

K.—After forging or machining heat to 1500° to 1550° F., quench, reheat to 1300° to 1400° F., quench, reheat to 600° to 1200° F., and cool slowly.

L.—After forging or machining carbonize at a temperature between 1600° and 1750° F. (1650° to 1700° F. desired), cool slowly in the carbonizing mixture, reheat to 1400° to 1500° F., quench, reheat to 1300° to 1400° F., quench, reheat to 250° to 300° F., and cool slowly.

M.—After forging or machining heat to 1450° to 1500° F., quench, reheat to 500° to 1250° F., and cool slowly.

P.—After forging or machining heat to 1450° to 1500° F., quench, reheat to 1375° to 1450° F., quench, reheat to 500° to 1250° F., and cool slowly.

Q.—After forging heat to 1475° to 1525° F., hold at this temperature one half-hour to ensure thorough heating, cool slowly, reheat to 1375° to 1425° F., quench, reheat to 250° to 550° F., and cool slowly.

R.—After forging heat to 1500° to 1550° F., quench in oil, reheat to 1200° to 1300° F., hold at this temperature for three hours, cool slowly, machine, heat to 1350° to 1450° F., quench in oil, reheat to 250° to 500° F., and cool slowly.

S.—After forging or machining carbonize at a temperature between 1600° and 1750° F. (1650° to 1700° F. desired), cool slowly in the carbonizing mixture, reheat to 1650° to 1750° F., quench, reheat to 1475° to 1550° F., quench, reheat to 250° to 550° F., and cool slowly.

T.—After forging or machining heat to 1650° to 1750° F., quench, reheat to 500° to 1300° F., and cool slowly.

U.—After forging heat to 1525° to 1600° F., hold at this temperature for half an hour, cool slowly, reheat to 1650° to 1700° F., quench, reheat to 350° to 550° F., and cool slowly.

V.—After forging or machining heat to 1650° to 1750° F., quench, reheat to 400° to 1200° F., and cool slowly.

TABLE III.—SPECIFICATIONS OF HEAT TREATMENTS FOR S.A.E. STEELS.

Specification No.	*Heat Treatments.*	*Specification No.*	*Heat Treatments.*
1020	A, B, and H	3335	P and R
1025	B ,, H	3350	P ,, R
1035	D, E ,, H	3320	L
1045	E ,, H	3330	P and R
1095	F	3340	P ,, R
2315	G	5120	B
2320	G, H ,, K	5140	H and D
2330	H ,, K	5195	P ,, R
2335	H ,, K	51,120	P ,, R
2340	H ,, K	5295	P ,, R
3120	G, H ,, D	52,120	P ,, R
3125	H, D ,, E	6120	S ,, T
3130	H, D ,, E	6125	T
3135	H, D ,, E	6130	T
3140	H, D ,, E	6135	T
3220	G, H ,, K	6140	T
3230	H ,, D	6145	T and U
3240	H ,, D	6150	U
3250	M ,, Q	9250	V
3315	G ,, M	9260	V

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